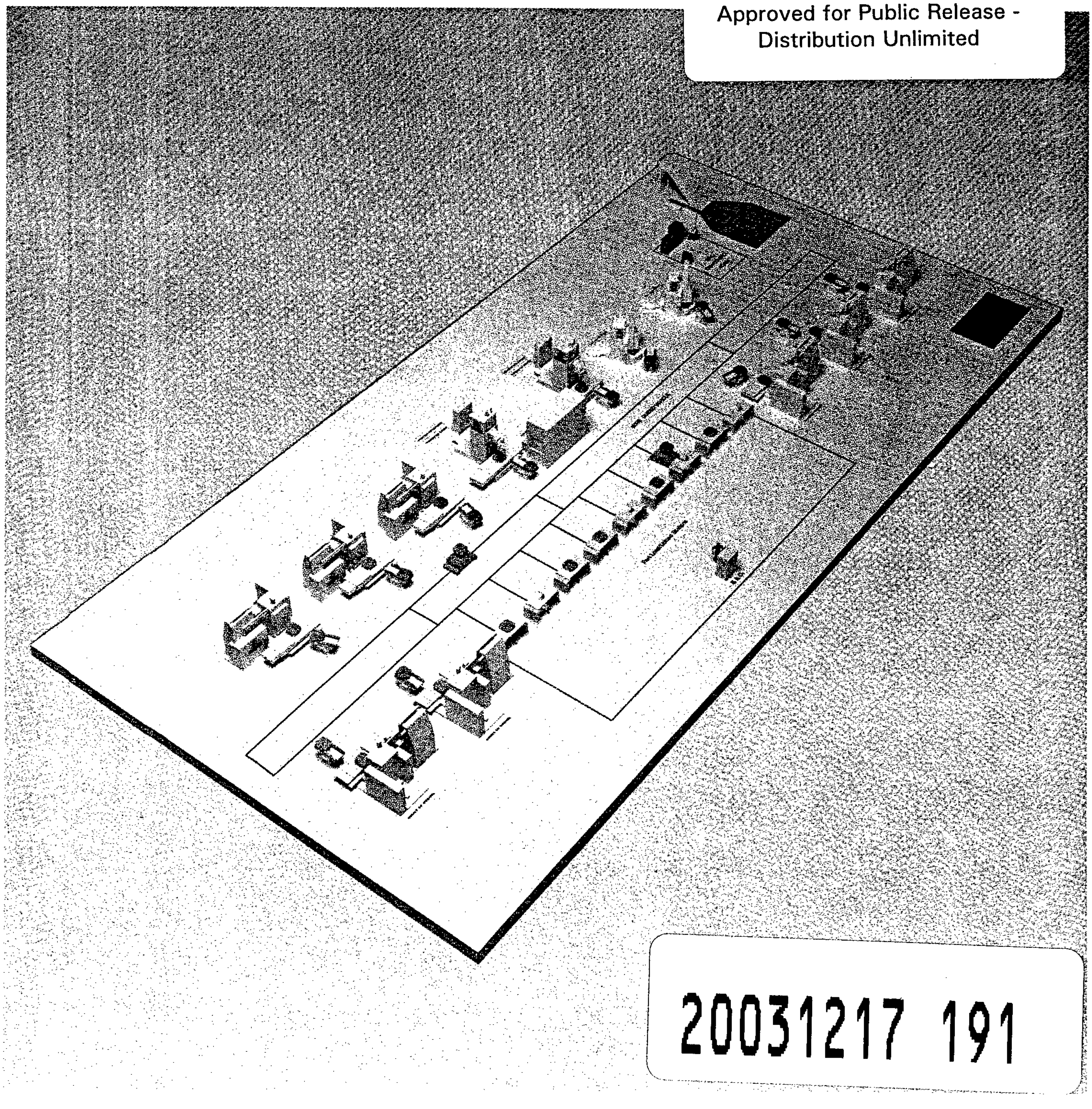
US Army

ManTech Journal

Retraining the Engineering Pool

Volume 9/Number 3/1984



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About the Cover:

Flexible Manufacturing System modeled on the front cover will provide automated handling and machining of scores of complex operations required to produce today's large caliber weapons. The system includes machining centers and vertical turret lathes, automatic inspection stations, and robot loading and unloading. Combining several machining operations into one flexible system will enable Watervliet Arsenal to customize all manufacturing operations as needed.

THE MANTECH JOURNAL is prepared quarterly for the U.S. Army under the sponsorship of the Directorate for Manufacturing Technology, DARCOM, by the Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, through the Metals and Ceramics Information Center, Battelle's Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201.

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Comments by the Editor


RAYMOND L. FARROW

Hosted by the U.S. Navy in Seattle, the 16th Annual Conference of the Department of Defense Manufacturing Technology Advisory Group (MTAG) will open on November 26 with a record number of attendees expected. The Conference has grown so steadily through the years, it soon will be so large a group that arranging for a suitable meeting place may become a problem. It speaks well of the import that previous attendees place on the past conferences that this attendance continues to grow. The annual conference provides a highly useful forum for industry and service manufacturing personnel to keep up with developments in the defense production base effort.

This year's Conference again features something special and of great interest to those in the manufacturing technology field. On Tuesday, November 27, the Special Topics Day presentations should arouse considerable discourse. The subject's titles in themselves would pique the interest of anyone who is involved with the planning and management of modern-day manufacturing operations. "The Factory of Today: In Place and In Fact", "The Factory of Tomorrow: In Development and Emerging", The DoD ManTech Program: Three Points of View"; and "The Industrial Modernization Incentives Program (IMIP): Three Perspectives" constitute a set of topics that should establish the thrusts of today in defense manufacturing prior to the Mini-Symposia scheduled for the following day of the Conference.

The latter two of the four topics listed above pertain directly to current DoD manufacturing technology programs and will be addressed on Tuesday morning, with the first two topics listed above discussed during the afternoon. There should be some interesting insights developed at these sessions.

A special feature of this issue of the U.S. Army ManTech Journal is an editorial by Fred Michel, Deputy Chief of Staff for the U. S. Army Manufacturing Technology Program at Army Materiel Command Headquarters. Some of the contents of this editorial on training our engineers to handle modern manufacturing operations prove most interesting. The vastness of the Army's production base is signified by the fact that the Materiel Command's fixed assets are greater—even after discounting land holdings—than those of the nation's largest companies, such as Exxon, General Motors, IBM, ITT, and other major oil and chemical firms. The current value of AMC's inventory of materiel is so many times that of any of these large corporations that it's apparent why our engineers face such an enormous challenge. The mantech programs being worked on will help reduce this immense inventory by providing capability to produce—on demand—required military hardware more quickly and efficiently. The training programs discussed for this cadre of engineers/managers represents an important adjunct toward successfully meeting the challenge.

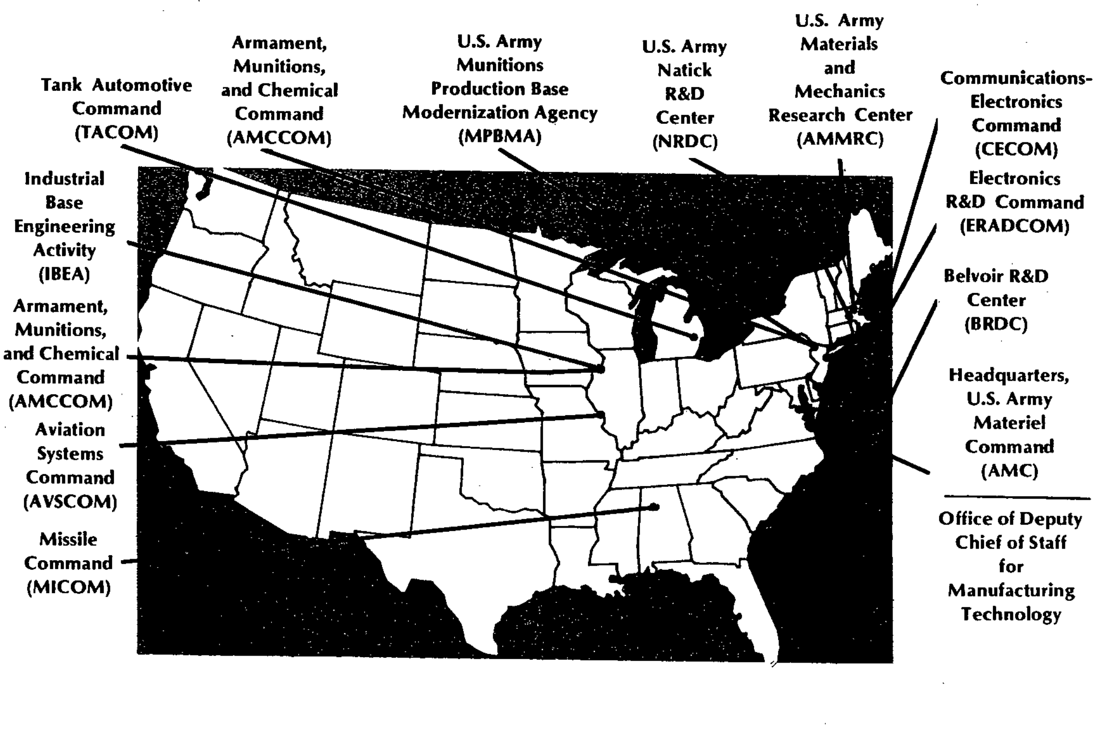
Other highlights of this issue of the Army ManTech Journal include a review of the Project REARM at Watervliet Arsenal and the new Flexible Manufacturing System being installed there. The first of Project REARM's two-pronged effort (an earlier report in this magazine gave an account of the Rock Island Arsenal portion of the effort), the Watervliet Project REARM is nearing its tenth year, going back to the earliest planning. This highly important program will keep our cannon manufacturing capability up to date, implementing the latest technologies.

In addition to a large number of brief status reports of ongoing Army manufacturing projects, this issue of the Journal provides in-depth reports on two very high-technology projects by the Missile Command.

The article on leadless components for printed wiring boards points up one more significant new development resulting from an Army mantech effort—one which will provide greater reliability in our battlefield electronics gear.

The article on the hardening of missile domes reports on a new technique for achieving greater effectiveness in the performance of our missiles. This new ultrahigh technology is described in excellent detail and should prove valuable to our readers.

AMC Manufacturing Methods and Technology Community



Preparing for the New Technologies

Manufacturing Training Underway

FREDERICK J. MICHEL currently is the Deputy Chief of Staff for the U.S. Army Manufacturing Technology Program. This office is responsible for the entire range of Army production engineering programs. He is a member of the Executive Committee of the Department of Defense Manufacturing Technology Advisory Group (MTAG), and until recently held the chairmanship of the CAD/CAM Subcommittee of the MTAG. He also represents the Army at the Manufacturing Studies Board of the National Research Council and is a board member of CASA/SME. Previously, he was employed by the Westinghouse Electric Corporation. He holds a Bachelors Degree in Mechanical Engineering from the City College of New York and a Masters Degree from Columbia University in the same field.

Visualize an employer with over 800 engineers engaged in a manufacturing activity encompassing the widest range of technologies imaginable, and scattered over an area of 2 million square miles. He is charged with the task of producing the materials for a modern military complex supporting the defense of the most diverse nation in the history of the world.

This employer would be ranked first both in inventory and in fixed assets (even excluding land) if he were listed among Fortune magazine's Top 500 firms, and eighth in terms of total sales. The value of his goods is almost twenty-three times that of large retail firms such as Sears or K-Mart.

The employer is facing the stark realization, as are many more organizations heavily engaged in manufacturing such as General Motors, General Electric, etc., that the value of the individual manufacturing engineer as a contributor is decreasing due to the frantic rate of change in manufacturing technology. The rate of obsolescence of skills is purported by those who study such issues to be increasing exponentially because of the widespread introduction of the microprocessor and software systems in manufacturing. The impact has been heightened by the relatively low cost of the microprocessor. This has led to the distributive approach, making it possible to operate the individual manufacturing cell independently from central data processing. Today, electronics is driving the technology on the factory floor.

The employer referred to above is AMC, the U.S. Army Materiel Command. AMC is initiating programs which are designed to accelerate the adaptation of its engineers to those new skills, as are its more specialized commercial manufacturing associates. The median age of the typical AMC engineer is probably somewhere between 45 to 55 years. Twenty-plus years have passed since that person received an engineering degree.

The change is driven by such new technologies as CAD/CAM or CIM, computer control, and robotics. They are the tools which will lead towards the factory of the future. Experienced engineers are both troubled and challenged by all those technologies. They are being adopted at a precipitous rate, as the pressure to lower production costs mounts. Therefore, it is necessary to accelerate the 10-year cycle which has been the norm for adoption of new technology in manufacturing endeavors. Several possible solutions are suggested:

- Formal schooling for special studies or for advanced degrees
- On-site training set up by local schools
- Training seminars
- Training courses offered by professional engineering societies
- On-the-site experience related to new technologies
- Existing AMC training programs.

Activities undertaken by AMC include some new and old programs as exemplified by the following:

1. **Advanced Manufacturing Engineering Studies Program**
A new initiative which offers an engineer the opportunity to undertake a full-time, graduate level program in manufacturing or manufacturing engineering. Typical graduate school requirements will involve 18 months to complete the course work and projects. All expenses are paid by the Army including full tuition, compensation, and health benefits. An increasing number of institutions across the country have established graduate level engineering programs with a concentration in manufacturing and production. The first AMC engineer on this program started at the Massachusetts Institute of Technology in September, 1984.

2. **Manufacturing Training With Industry (MTWI)**
A new initiative designed for engineers to gain direct experience in manufacturing. Civilian production engineers in AMC are selected for 1-year working assignments with industry. These engineers are given "hands on" manufacturing engineering assignments. Consequently, the AMC engineer is required to make a technical contribution to the manufacturing operation of the host firm. This precludes "observational" type assignments. As a result, the AMC engineer will acquire a first-hand appreciation of the effect of his effort on cost. At this writing, AMC engineers are working at Martin-Marietta and the John Deere Company. The program will be expanded as new nominees are approved.

3. **A Career Intern Program for Engineering and Pre-Engineering**
An existing AMC entry level engineering training program that will provide a participant the opportunity to complete the requirements for a Master of Science degree in manufacturing engineering. The courses are taught at the Red River Intern Training Center of AMC. Several universities are being considered to then provide additional courses, the combination of which with the Red River training will qualify the student for the advanced degree.

Gone forever are the days when a young engineer can enter the manufacturing arena and be certain of a comfortable, unchanging, lifelong career in engineering. Never again will acquired engineering competence alone offer a sure path to job security and ultimate retirement. Adaptation to change and continual development of new skills to handle new technologies will forevermore be the way of life for the Army engineer.

We at AMC plan to continue investing heavily in the establishment of long-term development programs for our engineers to carry them into the next century.

Old Blended With the New

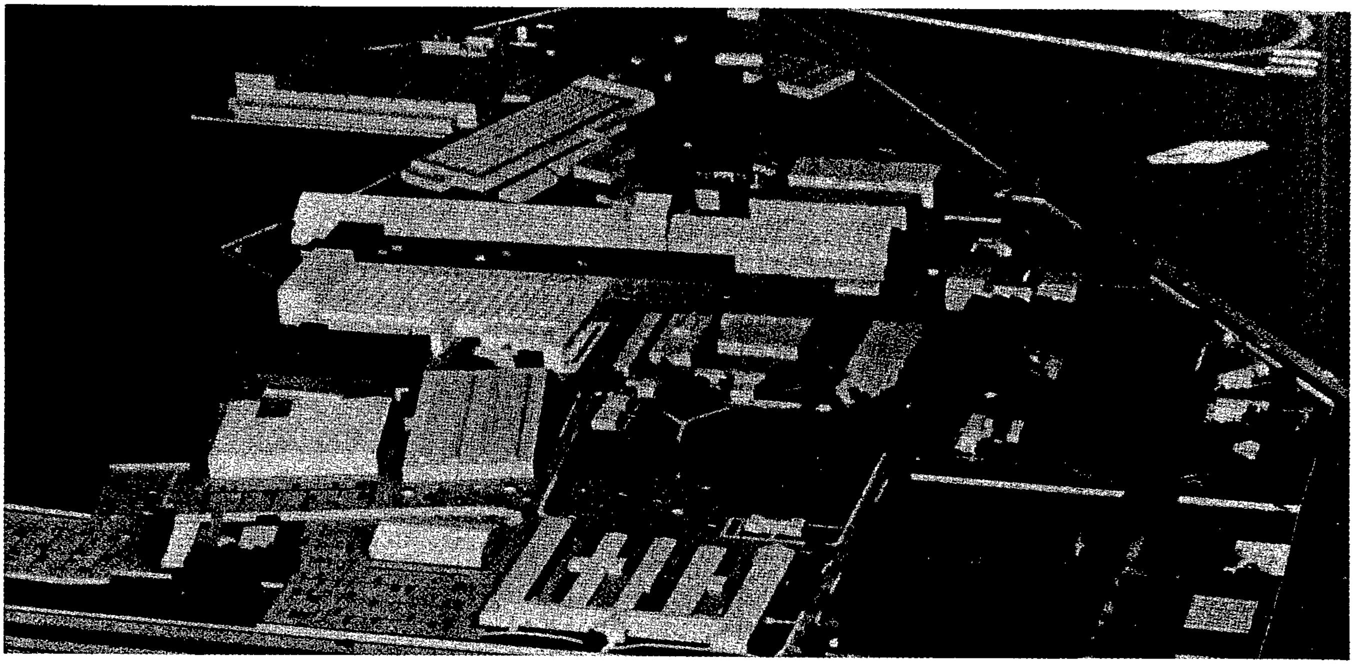
Waterveliet Arsenal— Past, Present, and Future

NOTE: The following article was prepared by staff of the U. S. Army ManTech Journal from materials provided by John E. Swantek, Public Affairs Officer at Watervliet Arsenal, Watervliet, New York.

Watervliet Arsenal has been producing cannon—large caliber weapons—for nearly 100 years. It has been producing ordnance material for more than 170 years.

Uneasy peace filled the years following the successful conclusion of the Revolutionary War. The long struggle among the great powers of Europe for mastery of the continent had created an instability in world affairs which more than once threatened to draw the young United States into the vortex. Attempts to keep America from becoming involved had failed and a series of incidents at home and abroad carried America at last to the threshold of war in the twelfth year of the new century. On June 18, 1812, Congress voted for war against England, in accordance with the President's recommendation. He had cited England's impressment of American seamen, violation of United States territorial waters and restraint of American trade. Congress had agreed: the country's only hope for redress of these wrongs lay in a resort to arms. The following day president Madison proclaimed the war, charging England "with a course of conduct insulting to the independence and neutrality of the U.S." Thus, the young nation which once had fought to gain freedom and rights was again at war to preserve them. Yet, England was a most powerful nation with large, veteran armed forces on land and sea, while the United States military establishment was almost nonexistent by comparison. The extent of the American wilderness frontier and seaboard was enormous and the army would have to be much increased to defend it. The task of arming these troops and providing their materiel support over these vast areas was given to the United States Army Ordnance Department, then a little more than one month old. The Ordnance Department selected one Arsenal to be located somewhere in upper New York State, so that materiel could be sent either north or west with the greatest speed, as the Americans expected to be attacked from the north at Lake Champlain and from the west at Niagara Falls. In the Village of Gibbonsville, which the Old Dutch settlers had called "Winter's Plantation," a very suitable plot was discovered. If the British struck at Lake Champlain, a portage of only sixty miles to the lake from the Hudson River would be necessary. If the enemy came from Lake Ontario, supplies could be shipped up the Mohawk River, and if New York were

NOTE: This manufacturing technology project that is being conducted by Watervliet Arsenal was funded by the U.S. Army Armament Munitions and Chemical Command under the overall direction of the U.S. Army Manufacturing Technology Program office of the U.S. Army Materiel Command (AMC). The Watervliet Point of Contact for more information is Mr. Gary Conlon, (518) 266-5737.



ARCHITECT's MODEL of Watervliet Arsenal after the completion of Project REARM shows the three main production buildings being added (dark colored.) Other buildings have been razed and the end result will be an integrated, thoroughly modern production plant capable of manufacturing high quality products for America right into the 21st century.

attacked, the Hudson furnished a means of quick shipment to the south. This was the perfect site.

Since then, there have been many changes. The Civil War and War with Spain. World War I. World War II. Korea. Vietnam. All brought challenges to Watervliet. New weapons were developed. New processes were needed to produce these weapons more effectively. Watervliet Arsenal has stayed in the forefront of cannon production.

Now, the Arsenal is undergoing the most comprehensive change in its history, through Project REARM (Renovation of Armament Manufacturing). This $250 million project will revamp the Arsenal's cannon manufacturing capabilities. Three major new production buildings and hundreds of new, up-to-the-minute manufacturing machines are changing the face of the Arsenal.

The problems facing Watervliet were common to many plants throughout the country: to take yesterday's factories and turn them into tomorrow's factories. Many of today's factories—particularly those located in America's industrial heartland, the upper midwest—have several things in common.

They have a lot of floor space in relation to annual production. They are old.

The equipment is outmoded.

In-process inventory is very high. There is probably more than 33 cents in total inventory for every dollar of sales. The inventory turn doesn't exceed 3 to 3½ times.

These operations cannot compete effectively with newer plants.

Project REARM Initiated

Preliminary work for Project REARM had begun in 1974 when Arsenal officials, well aware of the strain placed on manufacturing equipment and buildings by the demands of production for the Vietnam conflict—a problem made more serious by the fact that much of the manufacturing equipment dated back to the Korean War or even World War II—commissioned the Detroit, Michigan, engineering firm of Giffels Associates to conduct a thorough study of the cannon production base and the Arsenal's manufacturing functions and to make recommendations concerning the modernization of these facilities. This was to be done with a view to bringing all of these up to the state-of-the-art in order to increase production flexibility and provide an increased ability to respond to the demands of a national emergency.

The Giffels study, presented in June, 1975, concluded that considerable savings could be made by a realighment of plant equipment packages according to caliber rather than by individual weapons. Thus, plant equipment packages would be set up to deal with 155 mm weapons within that category for which mobilization responsi-

bility was assigned. Further, the studies indicated that lead times could be shortened and economies achieved by retaining the manufacture of all thick-walled cannon for peacetime, war reserve and mobilization at Watervliet Arsenal and procuring all thin-walled weapons—mortars and recoilless rifles—from other sources. Central to the savings possible through these recommendations would be the modernization of the buildings and equipment necessary to carry them out.

The first result of the Giffels study was an Arsenal military construction project to build two new manufacturing buildings and a new oil storage facility and to renovate several other buildings. Included was the demolition of several older buildings necessary to make way for the new construction. Plans were submitted also for the rehabilitation or replacement of 680 pieces of manufacturing equipment. Officials also hoped to acquire a large number of programmable numerical control machines.

The total Project REARM included requirements for both buildings and equipment. Construction was programmed in fiscal year 1979 that would involve demolition of some 19 obsolete buildings—many of them temporary wooden buildings of World War II vintage, construction of two major new manufacturing buildings, and an oil storage facility and renovations to six buildings.

For the Arsenal, fiscal year 1978 was pivotal for project REARM. While negotiations were going on during the first quarter between Lev Zetlin/Giffels, Inc., and the New York District Corps of Engineers to initiate design of the proposed buildings, the construction funds in the budget began to flounder.

Although the projct originally enjoyed a very high priority, a cutback in the Department of Defense budget resulted in the development of a new priority listing for all Department of Army and Department of Defense project requests. The Arsenal's modernization program came up during these discussions because contract award for Phases I and II of construction were scheduled for late in the fiscal year.

The final resolution came in mid-December, 1977, when Secretary of Defense Harold Brown briefed President Jimmy Carter and received guidance to prepare a $126 billion defense budget. This resulted in the budget approval line being drawn just above the Watervliet Arsenal project. Deferring the funding to FY80 could have resulted in a delay of up to one year in occupancy of the first new building, as well as inflated project costs and deferred accrual of projected savings.

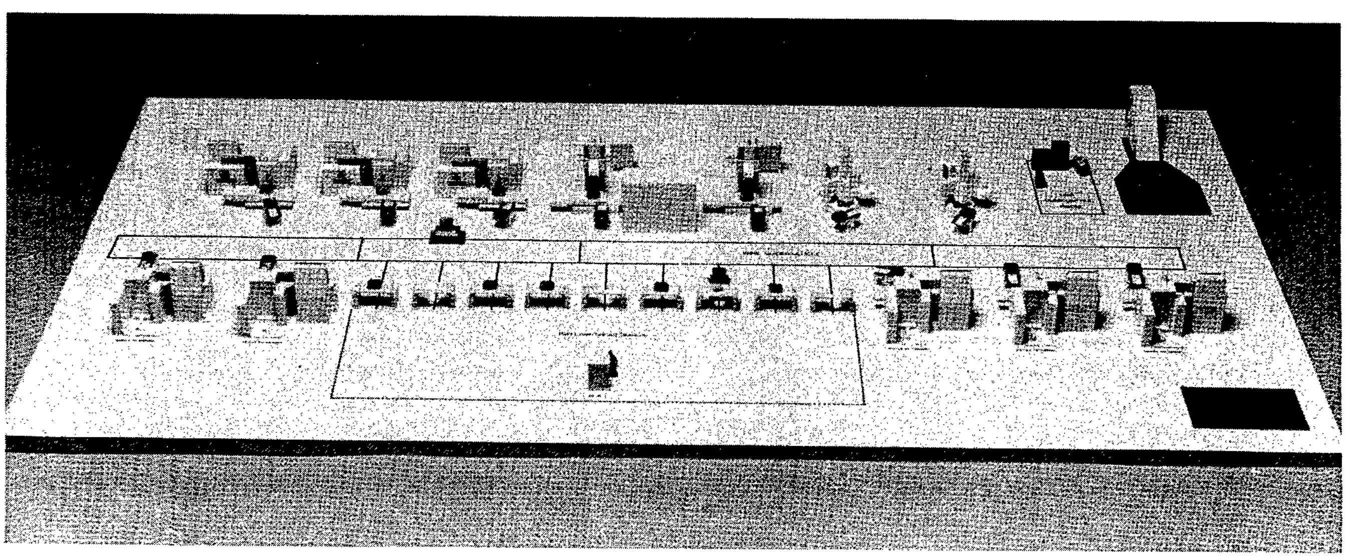
The $20.5 million for demolition and new construction was for the first year of a five-year building plan. The major demolitions would be made to Buildings 105 and 14, 19th century structures housing offices and small shop facilities; Building 30, the carpenter shop; the heat treat wing of Building 110; and a portion of Building 108 containing offices. Also scheduled for demolition were several small utility buildings.

The two major new manufacturing buildings would be added to existing Building 35. The west addition would be 110,000 square feet in size and would house facilities for medium caliber gun tube manufacturing. On the east side, 67,000 square feet would be added for heat treating, platting and supply operations. Construction would also include a new building for storage of petroleum, oil and lubricants, as well as renovations to six existing buildings.

Heritage Preserved

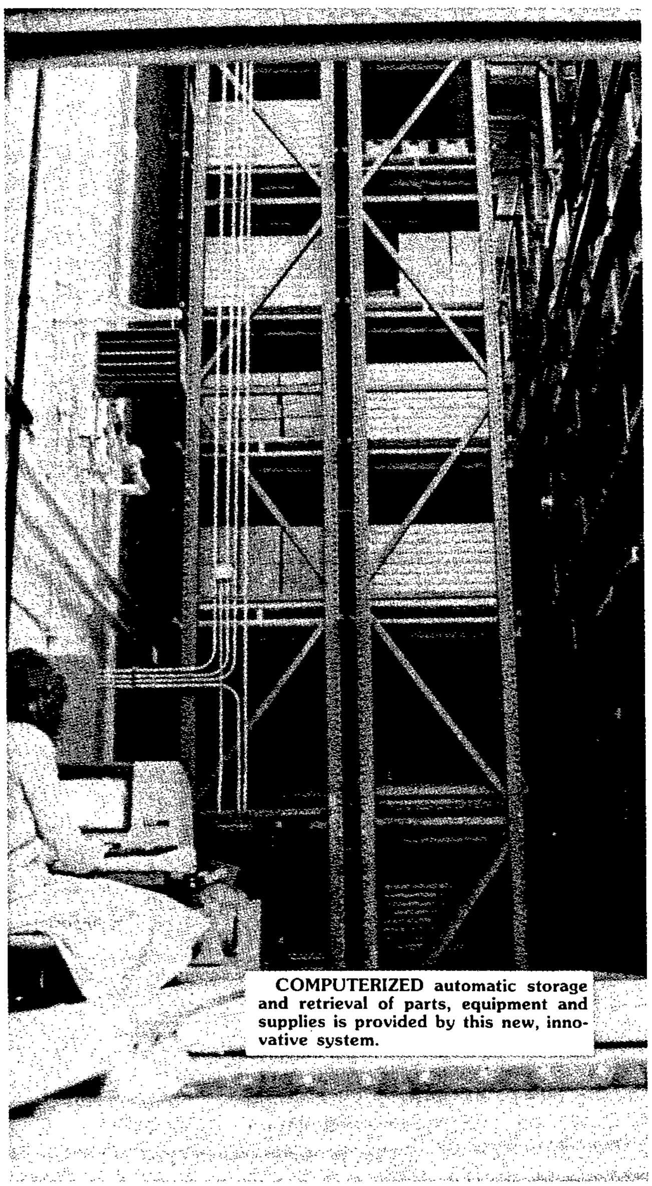
Because the Arsenal had been a Registered National Historic Landmark since 1966, the REARM demolition and construction plan required the concurrence of both the New York State Historic Preservation Officer and the Presiden's Advisory Council on Historic Preservation. To obtain these concurrences, the Arsenal prepared and submitted extensive documents detailing the impact, alternatives and mitigative measures that would be taken to preserve the historic nature of the Arsenal. These documents were fully coordinated with the New York State Historic Preservation Act of 1966 and other federal and state laws. This action was pioneer for the Department of the Army. The Arsenal's agreement represented the first ever concluded between a military installation and federal and state preservation officials. As such, it was touted as a model and precedent that would be followed and consulted by other military installations in the future.

Also approved in the fiscal year 1979 defense budget was $13.5 million for new and rehabilitated machines. This



marked the first installment of some $130 million for equipment that would be requested over a six-year period. REARM included plans for buying and rehabilitating several hundred machines. These included lathes, milling machines, grinders, threaders, broaches, presses and boring machines.

In May 1978, a master plan for Project REARM was published and distributed throughout the Department of the Army. The plan was based on 1982 mobilization requirements that related cannon and spare tube production to planned force structure and ammunition consumption rates. This plan established courses of actions needed to meet requirements based on economics, responsiveness, and the capabilities of both commercial and government facilities. In developing the plan, priority was directed toward those modernization efforts required to support planned peacetime procurement of tank guns and artillery.



COMPUTERIZED automatic storage and retrieval of parts, equipment and supplies is provided by this new, innovative system.

One of the most important components of the master plan was the equipment upgrading requirements. The results of the equipment condition assessment completed earlier were reviewed by Booz-Allen Applied Research, Bethesda, Md. In their final report, furnished in February 1978, Booz-Allen found that the criteria used by the Arsenal in determining equipment conditions were comprehensive and that the data supporting the priorities and budget estimates was accurate. Booz-Allen concluded that "there is substantial evidence for a large program to restore lost capability and to compensate for continuing wear and tear on at least 420 machines." To meet future peacetime production requirements and to provide a responsive and reliable emergency production capability at Watervliet Arsenal, the assessment showed the need for investments of more than $130 million for the purchase of 492 pieces of equipment and rehabilitation of 188 machines. The project requests for this effort were submitted in the Department of the Army's Production Base Support Program in January 1978, along with a strong Manufacturing Methods and Technology (MMT) program needed to insure that goals would be met.

In a fanfare marked by ruffles and flourishes, speeches by Army and Congressional dignitaries, and the climactic crash of a wrecking ball into Building 105, Project REARM got underway with a highly successful ground breaking ceremony on March 30, 1979.

Computer Aids, Robotics

Most of the new equipment obtained through Project REARM indeed is computerized. As computers become more a part of our daily home life, they are also becoming a integral part of the work life at Watervliet. Terms such as "computer-numerically-controlled," "computer-aided design" and "computer-aided manufacture" are commonplace. Even robots, once linked exclusively to science fiction movies, are being put to constructive work at the Arsenal. Modern industrial robots, however, look nothing like the human-shaped machines of the movies. Robotics in manufacturing usually means a system of levers and clamps which are controlled by a computer and perform complex movements within a manufacturing system.

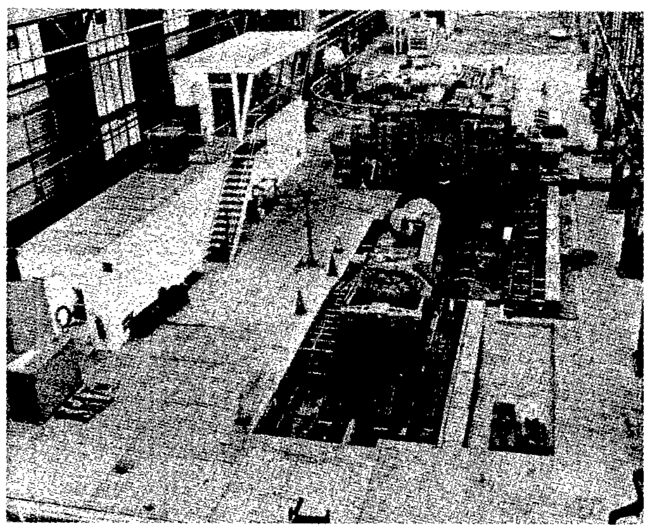
Flexible Manufacturing System

Typical of the state-of-the-art equipment being installed is a Flexible Manufacturing System. This massive manufacturing center—which is the largest single purchase ever made by the Arsenal—will automate several major operations in the manufacture of cannon components. The system includes machining centers and vertical turret lathes, automatic inspection stations, a washing station and a load-unload area where parts will be taken out of the system on pallets.

Scores of complex machining operations must be accomplished in the manufacture of today's large caliber weapons. Combining several machines into one flexible system will allow Arsenal operators to virtually customize manufacturing operations as needed.

Another futuristic addition to the Arsenal is the Automated Storage and Retrieval System, already in operation. This computerized system allows for the storage of supplies, components, parts and other items in high, vertical stacking bins. Items are stored and retrieved automatically by computer-directed cranes. An operator at a computer terminal tells the cranes where to store pallets. And, by pushing a few buttons, the pallets will be retreived automatically. This vertical storage makes the most efficient use of Arsenal storage sapce.

Computers will also become part of the daily routine outside the manufacturing areas. The number of computer terminals will increase as much as ten-fold in the next few years. The plan is for "data cells" to be set up within each of the Arsenal's major organizations. Computer programmers will be trained to produce software geared specifically to the needs of these individual Arsenal units. In addition, many Arsenal employees will be able to make use of these computer terminals in the course of their daily work without a great deal of technical training. Massive amounts of paperwork can be eliminated (along with the need to store this paperwork).



The Operations Directorate is the manufacturing element of Watervliet Arsenal. It is in Operations that a cylinder of steel is turned into a precise, well engineered, state-of-the-art large caliber gun tube.

A gun tube must be made of special alloy steel. It must be absolutely straight. Machining must be accomplished to fractions of an inch.

The Arsenal also manufactures the breech mechanisms for these gun tubes. This is the device at the loading end of the tube. Many parts must be machined to fit together to close tolerances.

It is the responsibility of the Operations Directorate to take the rough steel "preforms" and turn them into the finest large caliber weapons to be found anywhere.

The Operations Directorate is made up of four divisions: Manufacturing, Production Planning and Control, Quality Control and Supply.

The Manufacturing Division, of course, is responsible for the "hands on" work of manufacturing the finished product. Some of the special processes involved are mentioned below.

Production Planning and Control is responsible for planning, organizing, directing and controlling the production. This involves the use of modern management and engineering techniques to insure that Operations meets all of its contractual obligations and does so with the greatest possible efficiency and productivity. It is here that managers and engineers work to improve the processes and integrated systems of labor, material and equipment to produce the best product, on time and at the right price.

Quality Control aims at insuring that the finished product is of the highest quality. Through the efforts of this division, cost reductions are achieved by preventing defects in the manufacturing process.

Supply Division provides an important staff function. Here, supplies and equipment are warehoused and distributed not only within Operations but throughout the Arsenal.

The "big guns" produced at Watervliet are generally recognized as among the finest in the world. This is no accident. This quality is maintained through constant research and development, and new management and manufacturing techniques.

Revolutionary Technology

One of the most interesting new manufacturing developments is the use of rotary forge technology. This has revolutionized the manufacture of thick-walled cannon. The rotary forge, installed in 1975 at a cost of $14 million (and the largest of its kind in the world), can produce a gun tube forging in 10 minutes where it once took four-and-one-half hours!

A computer-assisted forge, using four massive hammers, pounds out the rough shape of a gun tube. The hammers, automatically controlled, develop a force of 1,100 tons, pressing 200 times per minute.

But the forging process only provides the rough shape of a tube. Many other important processes must be applied. The bore (inside the gun tube) must be chrome plated. The tube must go through a process called autofrettage, where, by means of a special process, the tube is made many times stronger. Machining makes the tube ready to receive the various component parts such as the breech mechanism and, if the particular gun calls for it, the muzzle brake. Both of these are also manufactured at the Arsenal.

Each of these processes has been developed and continually improved over the years. Even the special wooden

crates in which the guns are shipped are made at Watervliet.

In accomplishing these tasks, Operations Directorate makes use of the latest technological devices and processes. Black light and laser technologies are used to examine the work done on the guns. Numerically controlled machine tools are used. An automated plating facility makes that job more efficient.

FMS Buy Unique

In a landmark REARM procurement action, Watervliet Arsenal awarded a contract to The Manufacturing Systems Division of White Consolidated Industries of Belvidere, Illinois, for a $15.3 million flexible manufacturing system (FMS) which will automate several major operations on major cannon components here.

It is the largest single dollar-value procurement ever carried out by Watervliet Arsenal; the unique action took more than three years to complete.

The flexible manufacturing system will provide the Arsenal with an integrated computerized facility able to perform more than 50 percent of the major operations on breech blocks and breech rings for 105 mm, 120 mm and 155 mm weapons.

The FMS will be composed of major machine tools plus other state-of-the-art pieces of equipment, numerically controlled, of proven reliability and efficiency.

There will be machining centers and vertical turret lathes plus automated inspection stations, a washing unit and the associated load-unload area where parts will be put into and taken out of the system on pallets.

Within the system they will be moved from station to station on trolleys running along wired tracks in the floor which will direct them by magnetic impulses sent out by the command computer. The computer will also select the machine required for the necessary operation and give it its orders.

The Arsenal will have a system in between the transfer system production line you would see in a Detroit car plant where rows of identical machines perform identical operations on thousands of identical pieces, and a job-shop operation where a large variety of 'standup' machines perform a large variety of operations on relatively small numbers of pieces.

The flex complex will be a mid-volume system which will provide many of the advantages of both of the other systems and will suit very well the types and volumes of work which the Arsenal is called on, either in peacetime or mobilization.

Building 35 is the site at which the FMS will be installed, and the schedule calls for going into rapid action on preparations, with final acceptance for operation in April-May 1985.

The Arsenal expects to amortize the $15 million investment, or achieve 'payback', in about five years at peacetime production rates.

And 'payback' was the magic word in the unique, difficult, and eventually highly successful procurement procedure.

Instead of the normal low-bidder situation that has sometimes presented difficulties in government acquisitions, as a result of procedures worked out by Arsenal staff, a three-level system was used:

- The bidding was opened to all possible suppliers in the world;
- Three corporations, all American, were selected for the second screening;
- From these, The Manufacturing Systems Div. of WCI was eventually selected.

Instead of the normal low 'responsive and responsible', the selection was based on a complex matrix with points given for price, technical requirements, and 'payback' time.

The three companies finally considered were provided with virtually the whole technical data package for the components required and allowed to produce their own designs for performing the work.

After considerable lengthly negotiations over details, The Manufacturing Systems Div. of WCI was chosen as the best provider for the system the Arsenal needed, even though the company was not the low bidder.

The final agreement was for a system at a cost of $15.3 million, with equipment delivery to begin in 390 days and be complete in 800 days and a shortest-time payback of two years.

After eight months of preliminary planning, the procurement action began in September, 1979, with a pre-procurement conference between representatives of Procurement, Operations, Benet Laboratory, Management Information Systems Directorate, and advisors who continued to work in close cooperation until the completion of the action.

A bonus of the award was that the work on the FMS is being done by American subsidiaries of the parent com-

pany and is expected to benefit economically depressed areas in Illinois and Connecticut where they are located.

Oldest Continuously Active Arsenal

Watervliet Arsenal today is the oldest continuously active arsenal in the country. It is also among the largest, most modern and efficient large caliber weapons plants in the world. The Arsenal is the principle source for such weapons for the United States and many of our allies.

The 10 buildings on 12 acres of land which made up the original arsenal have grown into 91 buildings on 150 acres with more than two million square feet of floor space. About 2,600 people make up the "Arsenal Family" including the Arsenal proper and tenant commands such as the research and development facility, property disposal office (surplus) and communications center.

Watervliet Arsenal is the second largest industrial employer in the Capital District of New York. Located in Watervliet, a city of 11,300, and only six miles from the state capital at Albany, the Arsenal is in the heart of the northeast industrial corridor. There is abundant transportation, skilled labor and easy access to the country's major population centers.

Watervliet Arsenal is part of the U.S. Army's Armament Munitions and Chemical Command. AMCCOM is, in turn, a major subordinate command of the Army's Material Command—AMC. AMC consists of a nationwide netowrk of installations and subinstallations which is charged with the major task of keeping America's troops properly supplied with the best equipment and material. This means not only purchasing and supplying but researching, developing and manufacturing material needed by today's modern Army.

Watervliet Arsenal operates much like any other business. As part of the Army Industrial Fund, the Arsenal must be virtually self-sustaining. An initial capital investment was made to start the facility and now the Arsenal must produce a quality produce which can be sold at a competitive price and cover costs of manufacturing and other plant-related operating costs—just like any other major industrial facility.

In the case of the Arsenal, this initial investment of taxpayers' money has been a good one. The value of the original investment is estimated at $195.8 million. The replacement value is approximately $801 million.

Organization a Key Factor

Today's Arsenal is organized into several major departments called directorates with the heads of these directorates reporting directly to the commanding officer. (The Arsenal has always been commanded by an active duty Army officer, usually a colonel.) The largest operating unit is the Operations Directorate, which is responsible for manufacturing and direct production work. The Procurement Directorate takes care of orders for large caliber weapons and is responsible for value engineering, industrial readiness and mobilization efforts. The Product Assurance Directorate makes sure of the quality of cannon produced at Watervliet.

Ohter major organizational elements include: the Comptroller's Office, Civilian Personnel Office, Management Information Systems Directorate and Facilities Engineering Directorate (which is responsible for the physical plant.) The Benet Weapons Laboratory, a tenant command, is made up of more than 300 people engaged in research and development of processes and designs for large caliber weapons systems.

BENET WEAPONS LABORATORY's investment casting foundry is a unique facility. Here skilled craftspeople produce castings of small parts that would be impractical or impossible to purchase and intricately-shaped objects that would be too expensive to carve out of solid steel. Steel flows like water, in photo above, as molds are filled. Some of the steel "trees" or castings still connected by steel limbs are shown below.

The Basic Mission

The basic mission, the reason for the Arsenal's exisence, is to manufacture quality cannon and the speciall tools, test equipment and training devices needed to support modern large caliber weapons. For 100 years, quality cannon from Watervliet have been used on tanks, mortars, howitzers and recoilless rifles.

Watervliet Arsenal, through the Procurement Directorate, has the national cannon procurement mission. This means that, in addition to manufacturing cannon, the arsenal is the purchasing agent for the U.S. Armed FOrces for such large caliber weapons systems. Orders from branches of the Armed Services and U.S. allies are placed through Procurement.

The third major element of the Arsenal's mission is mobilization and industrial readiness. In the event of a national emergency, Watervliet Arsenal has to be prepared to meet an increased demand for its product. It also is responsible for providing designated private industrial firms with the equipment and know-how needed to produce increased numbers of cannon to meet the mobilization demand.

It is somewhat unusual for an installation of Watervliet Arsenal's size to be charged with such a national mission but the historical expertise and concentration on one principle product—cannon—has prepared the Arsenal staff for the challenge.

The process of meeting the mission begins with the Procurement Directorate, an Army term for what would be the purchasing office in private firms. The Procurement Directorate purchases cannon for the U.S. forces. Orders are received and placed in-house with the manufacturing division. Procurement also receives orders for cannon from foreign governments—allies of the United States—through federal offices in Washington, D.C.

The Procurement Directorate also purchases all materials used in manufacturing, supplies, plant equipment (especially important as new, modern equipment replaces the old machinery) construction contracting services and the like.

In addition to contracting for the best value for every dollar in purchasing, Procurement also conducts a Value Engineering Program which attempts to save the government money by engineering cost-saving features in Arsenal products and procedures.

Mobilization Procedure

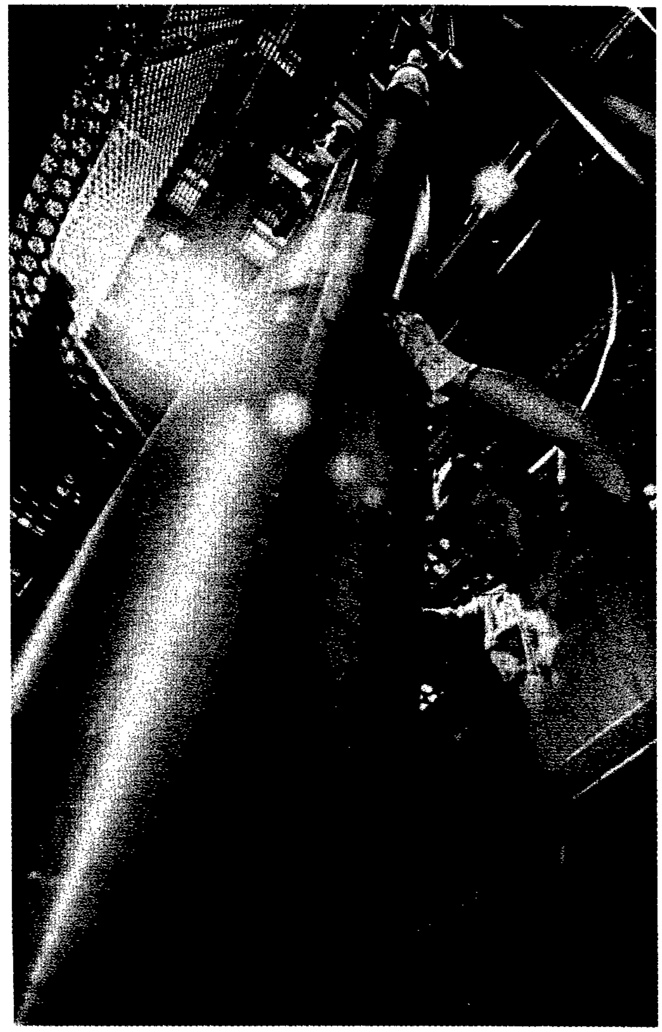
A major responsibility of the Procurement Directorate is planning for mobilization. Cannon needs during a national emergency are determined and then Procurement determines how that demand will be met. The Arsenal, operating at peak capacity, cannot meet the total estimated demand, so Procurement must line up private industrial firms willing to take on the manufacture of cannon during an emergency.

Overall, Procurement makes annual purchases totaling $50 million. About half of that amount goes for the purchase of forgings for cannon tubes and other major components. Minor components used in manufacturing account for another 15 percent. General supplies and materials make up about nine percent. The remainder goes to pay for everything from construction and new plant equipment to water and electricity.

From Procurement, an order goes to the Operations Directorate, where the actual product is produced in the Arsenal's modern plant.

Products

Watervliet Arsenal is the nation's cannon factory. As such, the Arsenal is equipped to produce cannon with bore diameters from 20 mm (less than one inch) up to the massive 16 inch guns of battleship fame. At one time or another, the Arsenal has manufactured just about every size cannon in between.



The current mission is to produce cannong used on self-propelled and towed artillery and on the tanks of our Armed Forces. Among the principal products manufactured at the Arsenal are:

- 40 mm Gun
- 60 mm Lightweight Company Mortar
- 4.2 inch Mortar
- 81 mm Mortar
- 105 mm Gun for the M60 Tank
- 105 mm Howitzer
- 120 mm for the new M1 Tank
- 155 mm for Howitzers
- 165 mm Gun
- 8 inch Howitzer.

In addition to these basic gun tubes, the Arsenal manufacturers the various base plates and mounts for the mortars and the breech mechanisms and tube assemblies for the large weapons systems.

Many of these large caliber weapons have been designed by the Benet Weapons Laboratory and are produced only at Watervliet.

The 60 mm Lightweight Company Mortar is a prime example of the close cooperation between the research-development and production elements. This modern weapon in general use by the Army can be fired from a baseplate on the ground or can be hand held. It weighs much less than previous company mortar systems—only 18 pounds in the hand held mode.

The largest of the weapons currently in production is the 8 inch howitzer. This gun is used on the M201 self-propelled howitzer system.

Among the newest of Watervliet's products is the 120 mm gun for the M1 Abram tank, the Army's new main battlefield tank. The prototype guns were manufactured at Watervliet and the actual production models are now coming off the line.

The largest guns ever built by Watervliet are the massive 16 inch bore diameter guns last used on Navy battleships. These guns weight more than 100 tons and measure up to 70 feet in length. Their accuracy and range are well known. They are capable of firing a projectile weighing 2,000 pounds over a range of more than 20 miles.

The battleship version, however, was not the first. During the Spanish-American War, the Arsenal produced 16 inch guns called Seacoast Cannon. These were designed and built to line America's coastline to protect against attack by enemy ships. (The Arsenal's "Big Gun Shop" was once called the "Seacoast Cannon Shop.")

The cannon produced by Watervliet Arsenal are purchased by the Army, Navy and Marines. Through special arrangements made by the federal government, cannon are also sold to foreign countries—allies of the United States.

Several other countries are equipped to manufacture thick-walled cannon and Watervliet must compete with them. This means that the product must be produced at the right price and, most importantly, it must be of the finest quality.

Research and Development

Research and development have played a strong role in the success of Watervliet Arsenal. Innovation and new technologies have been sought as a means for producing new and better products at lower cost.

This history of research and development was formalized in 1962 with the dedication of Building 40 as the Benet Research and Engineering Laboratories, known simply as Benet Weapons Lab. Several years later, two additional buildings were equipped to house scientists and engineers as the program expanded.

The research and development facility is named in honor of two men who played major roles in the development of Army ordnance and are closely tied to the Arsenal's history. Brigadier General S. V. Benet had served for 17 years as chief of Army ordnance. His son, Col. J. Walker Benet was commanding officer of Watervliet Arsenal from 1919 to 1921. Col. Benet's sons, Stephen Vincent and William Rose, became two of America's finest authors. In fact, Stephen Vincent Benet wrote part of his first book while living in Arsenal quarters.

Benet Weapons Laboratory conducts research, testing and extensive prototype production of large caliber weapons. The scientists and engineers of Benet focus on the study of materials, mechanics, mathematics and metallurgy. Their research and development facilities have access to the free world's bank of scientific literature in all major disciplines through a link up with the Army's most advanced computer system.

There are three divisions: Research, Development, and Processes. The Research unit develops new knowledge about weapons and the materials used to build them. The Development division designs advanced weapons systems from concept to proven design. It also provides the technical data and documentation needed to make these weapons ready for production. The Processes unit develops special machines and equipment to reduce costs, improve the quality and increase the productivity of weapons manufacture.

Benet Weapons Laboratory has some of the finest scientists and engineers to be found in any research and development facility. More than a third have advanced degrees. The three principle disciplines are mechancal and general engineering, mathematics and metallurgy-materials engineering.

The mechanical and general engineers design hardware, develop and test new guns, mounts, loaders, and recoil and breech mechanisms, also metallurgical techniques and new manufacturing processes. Mathematicians analyze models and simulations of weapons dynamics and stress analysis.

Benet research and development involves not only practical development of new weapons and processes but pure research into the properties of metals which may have applications in many other industrial and research areas. Many papers are published by Benet's staff and they are sought for participation in national and international conferences and symposiums.

The Benet scientists and engineers are involved in the age-old quest of cannonmakers—finding the maximum strength to weight ratio. The object is to build the strongest gun at the lightest weight. Soon after the dedication of the Benet building, a finding was announced which was a portent of the quality of research to follow.

"Whiskers" were used for the first time on an experimental basis. These "whiskers" are tiny crystals of various metals which are "grown" in high temperature furnaces and used to strengthen cannon-making materials. This works much like the reinforcing rods used in concrete building construction.

In 1967, a process for anodizing the surface of titanium components and, later, for successfully coating titanium with an energy-absorbent material was put to immediate use in helicopter construction.

One of the main achievements of the Benet staff has been the successful use of a process called autofrettage. Failures of some 175 mm guns in Vietname had caused the Army to reduce the safe firing life of these guns from 1,200 rounds to 300. This put great pressure on the Arsenal to produce four times as many guns at great expense. Benet researchers were able to apply the autofrettage process of prestressing the walls of the cannon barrel, which restored the 1,200-round lifespan. First year savings wer estimated at $21 million and an equal amount was saved over the next 10 years.

Benet scientists and engineers have been honored 10 times with the Army Research and Development Award—the highest Army research honor. In 1969, three researchers were given the award for their work on the theory of the mechanics of solids. In 1971, five Benet people won the award for their investigation of fracture mechanics problems in thick walled cylinders.

Guided Boring, Simulated Firing

Toward the end of the Vietnam conflict, one Benet scientist was credited with the "most significant new process to be introduced into gun-making in three decades." This was the development of a guided boring system. Boring and cutting tools were successfully married for the first time to electronic sensors. This meant that a bore hole could be cut lengthwise through a 36-foot long forging of super hard steel with a deviation in straightness of less than five-thousandths of an inch—the thickness of a razor blade.

Another dollar-saving process came out of Benet in the mid-1970s. The replication of the high pressure conditions present in a cannon tube when it is fired made it possible to test gun tubes without actually having to fire them. In the first three years of use, this high-pressure testing saved the Army more than $90 million. The process was later adopted by the British and German governments. And Benet earned yet another Achievement Award.

As the new decade of the 1980s dawned, Benet was honored again with the Army Research and Development Achievement Award. This time for the development of the 60 mm Lightweight Company Mortar system. The new system has the same range as the old 81 mm mortar, but it weighs only 45 pounds fully mounted, or less than 18 pounds in a hand-held mode.

Benet Weapons Laboratory continues to explore innovative ways to produce better weapons for the security of America while finding ways to reduce costs and discovering new scientific frontiers.

Most Important Asset

All of this modern equipment is useless unless people are trained to put it to good use. The Arsenal has one of the largest, most specialized pools of armament talent. Generations of local families have learned their skills and plied their expertise at the Arsenal. The Arsenal's Apprentice Training Program has been training machinists and other trades people for more than 75 years—the oldest continuously active apprentice school in the nation. Apprentices are put through their paces in rigorous four-year program which includes classroom work in math, science and related subjects as well as on-the-job training in Operations shops.

It has been said that the real "big guns" of Watervliet are its people. Nowhere is this more true than within the Operations Directorate.

The resultant combination of new facilities, new equipment and new skills for people will keep Watervliet at the forefront of manufacturers of large caliber weapons. This combiantion of resources also means the Arsenal can face the future with confidence. If future ordnance developments mean that traditioinal cannon are replaced by some new weapon, the resources of Watervliet Arsenal will be ready. Just as the Arsenal made the transition from making horse harnesses during the civil War to producing the big guns for World War I, so, too, will it be ready for a future transition.

For the foreseeable future, however, Watervliet Arsenal will continue to produce the finest large caliber weapons in the world—on time, safely and efficiently.

Historic Landmark

The entire Watervliet Arsenal is on the National Register of Historic Landmarks. Not just a building or two but the entire 150 acre installation. This is in recognition of the historic value of the Arsenal facilities, but it also is a tribute to the continuous development and present-day value of the Arsenal as a large caliber weapons production facility.

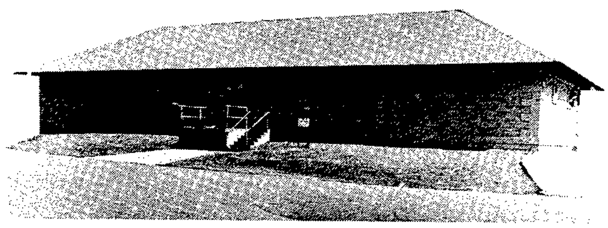
The real historic value of Watervliet Arsenal is its ability to convey the steady transition from early 19th century industrial techniques to up-to-the-minute manufacturing technologies. One or two buildings may not be historically significant in themselves but if they help show the development from one historical period to another they may be priceless.

The Arsenal tradition is one of preserving and making use of the past while blending it with the future. The original Big Gun Shop, Building 110 of the Arsenal, was built in 1889-1891, yet it stands only a few yards away from the new Building 35, one of the most modern industrial spaces to be found anywhere. And Building 110 continues to be a productive facility with changes in layout and equipment not affecting the historical value of the structure itself.

There are many architectural treasures. The original Powder Magazine with its four-foot-thick walls (to prevent accidental explosions from ripping through the walls and injuring workers in the days when powder was stored there) is now used as a laboratory. The present Officer's Club, a restaurant open to all employees, was built in 1840 as a laboratory. Quarter's No. 1, built in 1842, is still the residence of the commanding officer. The Iron Building, the only prefab cast iron warehouse building left in the United States, houses the Arsenal Museum and is a "must see" for students of architecture, history and civil engineering.

Even the massive Project REARM, the modernization program which aims at preparing the Arsenal for the 21st century, has been carried out without detriment to the historic value of Watervliet Arsenal.

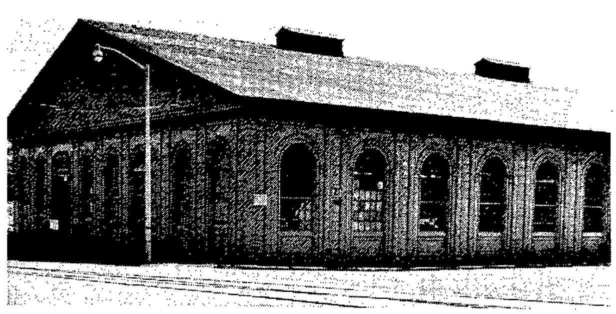
ORIGINAL POWDER MAGAZINE (1828)



OFFICER'S CLUB (1840) FIRST LABORATORY BUILDING

QUARTERS NO. 1 (1842) COMMANDER'S RESIDENCE

IRON BUILDING (1859) PREFAB CAST IRON WAREHOUSE



Brief Status Reports

Project 5068. New Anti-Corrosive Materials and Techniques (Phase III). Test vehicles have completed 20,000 miles of road tests without incident. A final report on this phase is being prepared. Procurement action was initiated for Phase III, long term marine environment exposure testing. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6038. High Deposition Welding. Flux core welding, H-plates welded. Submerged are welding parameters established. Narrow gap welding equipment being adjusted. Plasma M16 equipment being selected. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6054. Advanced Metrology Systems Integration. The state-of-the-art metrology system was completed. The needs analysis and SOA report are in process. Function models of current factory practice as revealed by industry surveys have been reviewed and approved. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6059-02. Self-Threading Fasteners. Program schedules completed. Areas of evaluation have been selected. Fasteners have been selected for testing and laboratory analysis. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6059-03. Adhesive Bonding. Program budgets and schedules completed. Production areas to be evaluated have been identified. Adhesives have been procured and laboratory testing has been initiated. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6059-06. Laser Heat Treating. Fixtures and optical tools have been fabricated. Laser heat treating and metallurgical testing has been initiated. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6059-08. Production Methods for Composite Turret Basket. Prototype fabrication was initiated. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6059-20. CARC Application Processing Technique. Paint test plan has been completed and approved. Robotic painting equipment has been procured, installed and debugged. Paint testing is continuing. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6067. Frame Welding Fixtures. Procurement package prepared for contractor effort. Contract has been awarded for the system design. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6076. Automated Depot Inspection of Roadwheels. The system was delivered to RRAD for acceptance testing. All road wheels scheduled for destructive testing thru May '83 will first be ultrasonically tested. The NDT data is being compared to establish the correlation factors. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6079-01. Monocrystal Alloy for High Pressure Turbine Blades. Tooling for first stage turbine blades shipped to TRW. Casting process definition has been completed. Solid blades are currently being evaluated by Avco Lycoming. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6079-02. Rapidly Solidified Technology -RST- Nickel-Base Superalloy. CAP process definition and CAP variability study have been completed. Different reductions in cross-rolling and heat treatment processes have been evaluated to establish the best combination of mechanical properties and microstructures. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6079-03. Bi-Cast High Pressure Turbine Nozzle. CAP process definition and CAP variability completed. Reductions in cross-rolling and heat treat have been evaluated to establish the best combination of mechanical properties and microstructures. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 6090. Tooele Army Depot Productivity Improvement Program. The majority of the preparatory work for the IPI program has been completed. The project is now awaiting further

funding enabling Phase I to begin. For more information, contact Don Cargo, TACOM, (313) 574-6065, 6378.

Project 5109. Precision Low-Cost Saw Delay Lines for UHF Applications. Phase II follow-on. TRW is establishing a pilot line to verify production techniques for saw devices. New go no/go routines point out deficiencies during and at end of fabrication process. Per unit cost will be reduced by a factor of ten. For more information, contact Joseph Key, ERADCOM, (201) 544-4258.

Project 5151. Liquid Phase Epitaxy of HGCDTE For Common Module Detector Arrays. Contractor will adapt liquid phase epitaxy (LPE) process for growing mercury-cadmium-telluride films on a production line for common module detector arrays. Will replace bulk-grone MCD arrays. For 60, 120 and 180 element arrays. For more information, contact Joseph Key, ERADCOM, (201) 544-4258.

Project 5174. CAM Sputtering Control for ZNO. A survey of manufacturers of computer controlled mass spectrometers was conducted. Procurement specifications were sent to industry. A search for a process that would benefit from CAM and would welcome our support has begun. For more information, contact Joseph Key, ERADCOM, (201) 544-4258.

Project 5180. MMT for Metal Dewar and Unbonded Leads. Honeywell and Santa Barbara Research Center will develop production processes for their respective metal dewar designs. These dewars replace the fragile glass design currently in use in the common module dewar. For more information, contact Joseph Key, ERADCOM, (201) 544-4258.

Project 5183. Production of Large Silicon for Laser Seekers. The westech zoner at Hughes produced two 3 inch diameter ingots. Resistivity test began at NBS. There is a delay in fabrication of split coil. Hughes is currently selling 1 inch diameter detector grade silicon to T.I. and Texas Optical Corp. For more information, contact Joseph Key, ERADCOM, (201) 544-4258.

Project 5193. Process Adjustments for Environmental Stress on Electronic Circuit Metals. Contractor is analyzing surface kinetics of electronic materials as they age. The firm is obtaining field data and defining chemical reactions, corrosion products, and film chemistry. An aging test is sought and will be validated. For more information, contact Joseph Key, ERADCOM, (201) 544-4258.

Project 5196. Industrial Productivity Improvement—Electronics. Harris Corp. is analyzing their government information systems division for areas of improvement in both manufacturing and business systems. Will specify an approach for an efficient manufacturing capability. For more information, contact Joseph Key, ERADCOM, (201) 544-4258.

Project 7807. Programmed Optical Surfacing Equipment and Methodology (CAM). Polishing time reduced from 15 to 2 min. Breadboarding of process control interferometer and assembly/testing of auto lens blocking device in progress. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 7916. Application of Low Cost Mandrel Materials. The subsized marage 350 mandrels coated with titanium oxide exhibited excellent adherence and hardness. A 105 mm mandrel is being detonation spray coated with tungsten carbide for forging trials. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 7926. Hot Isostatic Pressing (HIP) of Large Ordnance Components. Two hipped low alloy steel billets received. Material currently being analyzed for chemical, metallurgical and mechanical properties. One preform finished machined into 8 inch M201 breech block. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 7927. Generation of Base Machining Surfaces. The contractor, Computer Technology Corp., is currently involved in final assembly and testing of the equipment. The mechanical systems are 90 percent complete with four of the six axes functioning. The computer console and software are complete. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 7928. Robotized Benching Operations (CAM). Work is progressing in development of robot programming language with completion in site. Also the data for the data base for the 8 in breeching coordinates is also nearing completion. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 7940. Synergistic Platings With Infused Lubricants. Assembly of the facility for plating electrodeposited nickel phosphorus alloy was completed. The composition and operating condition of the developed bath has been identified. LFW-1 wear test specimens were coated for comparison to electroless nickel. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 7949. Application of Group Technology to RIA Manufacturing (CAM). Part families for machined parts have been identified. Three of the part families are currently being analyzed. It appears the results of this program will be integrated into process planning functions. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 7963. Group Technology for Fire Control Parts and Assemblies. GT scheduling program conversion is complete. The program is now available in fortran. A copy of the ICAM-GTSS software was requested. This software will be integrated with the present system. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 7985. Small Arms Weapons New Process Production Technology. Physical work on ultrasonically assisted ejector drilling completed. Testing for ultrasonic gun drilling has begun. Testing related to single point chamber contouring has been inconclusive due to tooling problems. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 7985. Small Arms Weapons New Process Production Technology. An updated quote from GFM of America is being obtained and a supply of H-11 material with a homogeneous carbide distribution is on order for the cold forging of chambers task. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 8017. Pollution Abatement Program. The batch type recycling system for cutting fluids has been in full operation. About 120 machines have been cleaned up and placed in the progrram for periodic pump out and recycle. These machines have all used one particular fluid. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 5071-78. Automation of Analyis of EMI Data. The format for inputting EMI data to the data base has been established. Time to cost estimate for adding frequent allocation to equipment file (FABF) data to the computer data base was determined. For further details refer to final report. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-101. General Purpose Transportability Test Area. The MTD divisions most involved in transportability testing were identified. The requirement statement was prepared. Procedures were developed for obtaining assistance from MTMCTEA relative to testing of items for transportability. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-59. Solar Powered Instrumentation Van. The 3KW, 30KW hour solar cell power system has been delivered to WSMR from DOE for use with instrumentation van. The SCPS and instrumentation van are undergoing evaluation. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-76. Gamma Dosimetry Improvement and Modernization Program. A major portion of the gamma dosimetry processed during FY82 was in production support of the M1 abrams and BFU system. A major portion of work will be devoted to placing in routine operation microdosimetry for linac testing. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-90. Toxic Gas Analysis by Gas Chromatography. The prototype heating flushing system was modified. The im-

proved system will eliminate small leaks which occur when prototype is under high vacuum. An analyzer, based on an available laboratory infrared spectrophotometer was built. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-96. Calibration Procedures for TV Tracking System. Field data was acquired and statistically evaluated. Modified calibration techniques have been proposed including instrumentation procedures and data reduction techniques. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-97. Improved Methods for Performance Testing Mortars at Extreme Temperatures. As a result of meetings with artillery weapons specialists, preliminary chamber design has been developed. Pending further funds, the chamber will be fabricated from wood to verify the dimensions and interior clearances required for gun crew personnel. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-01. Acceptance Test Procedures. The central library for the total ATP program was maintained. The master ATP index and the ATP index supplements were published and distributed. For more information, contact John Gehrig, TECOM (301) 278-2375.

Project 5071-37. Roll-Over Tests of Military Vehicles. The first phase of this investigation was completed by Varigas Research, Inc. The report revealed 5 types of army vehicles were identified as having a high turn over history when involved in emergency maneuvers. The second phase is on-going. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-43. Test Automation. Several projects within this subtask have been completed. Some of the subtasks are avionics test, antenna pattern, and digital communication. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-60. Receiver Operating Characteristics Measurements. The first phase of the ROC methodology investigation has been completed. The investigation is in suspension until equipment is purchased through the instrumentation acquisition program in FY84. For more information, contact John Gehrig. TECOM, (301) 278-2375.

Project 5071-67. Interoperability Test Methodology. Testing has been completed and the final report has been submitted. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-71. Improved Copper Crusher Pressure Gages. The internal ballistics division., BRL, has completed its analysis of the gage parameters using finite elements as its means of analysis and an initial design has been completed. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-77. Electromagnetic Radiation Effects and Susceptibility of Army Materials. Several methods have been investigated for using the EMRE fac. Fiber optics data links for OPSEC communication and automated control of test item function was done. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 5071-95. Rapid Determination of Environmental Hazards. Work continued on the preparation of a comprehensive report dealing with rate and persistance of GB and VX in soil, water and vegetation. The first draft is complete. Work is continuing on the task. For more information, contact John Gehrig, TECOM, (301) 278-2375.

Project 6350-1802. M732 Field Artillery Fuze/S&A Transportation Vibration Test. The 18K shortfall to complete the project was obtained from AMMRC. Testing is continuing on four new groups of S&A devices. The measurements and data analysis are completed for the report written. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2224. Automated Antenna Pattern Measurement. The fabrication and testing of computer interfaces and their integration into the measurement system is completed. All major components of this system have been received and meet system requirements. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

be recorded. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2944. Protective Mask Canister Electromagnetic Inspection Procedures. The tester has been assembled and tested at the contractors facility. It performed in an acceptable manner in detecting fissuring and wall thinning type defects. Final debugging and reproducibility runs is finished. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2802. Pyrotechnic Ingredient Acceptance Test. Investigated means of determining the reactivities of metals by thermal analysis. Found that proposed test was not reproducible due to inability to obtain uniform oxidation of metals in thermobalance crucible. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2820. Integrated Focal Plane Module Test Station. The DEWAR was received and checked for leaks, continuity and temperature control. The original controller was found to be faulty and replaced. Problems remain with cabling, the DEWAR configuration and the cold shield. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2826. Liquid Chromatographic Analysis—Nitrocellullose Base Propellants. The progress of this project was presented to the JANNAF propellant characterization subcommittee in April. The work was well received and over 15 requests for reprints of the paper and previous reports were received. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 0904. Chemical Remote Sensing Systems. The interferometer design has been completed. Initial development testing indicated that the instrument was compatible with the XM21 military requirement. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 0905. Manufacture of Impregnated Charcoal-Whetlerite. Contract was awarded to Westvaco Corp. for design of pilot plant. Contractor completed review of government data and has begun set up of equipment to prepare samples. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 0909. Automated Agent Permeation Tester. Prototype has been assembled and component debugging is being conducted. Safety assessment and operating instructions are being reviewed. Preliminary demonstration was conducted. For more information, contact Richard Koppenaal, MPBMA, (201) 734-3551.

Project 0913. Spin Coating of Decon Agent Containers. Materials which were compatible with D52 were evaluated. For more information, contact Richard Koppenaal, MPBMA, (201) 734-3551.

Project 1001. Pilot Line for Fuze Fluidic Power Supplies. The test equipment designed and constructed under Phase II was completed. Fluidic generator performance changes dictated hardware changes in the machine. After completion of engineering changes the program was documented and finalized. For more information, contact Richard Koppenaal, MPBMA, (201) 734-3551.

Project 1318. Production, Fill, Close and Lap 8 in XM736 and BLU 80 Bomb. The Toledo weight system was installed at the pilot plant and the accuracy was evaluated. Two enclosures were fabricated to protect the QL from the effects of moisture during transfer and filling operations. Technical report is available. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 1348. Super Tropical Bleach. Work was completed on pre-pilot evaluations and optimization of the liquid reactor double salt process. Engineering design for the process has been completed. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 1353. Smoke Mix Process (Glatt). Prepared engineering change proposal and draft notice of revision for configuration control board. Prepared final technical report with incorporation of TECOM test results. For more information, contact Richard Koppenaal, MPBMA, (201) 724-3551.

Project 6350-2401. Cannon Tube Automatic Magnetic Borescope Inspection. The redesign of the scanning probe has been sent to the contractor for fabrication. Also, a number of system electrical problems were diagnosed and repaired. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2418. Half Life of Tritium Lamps. The technical work has been completed. The technical report is available. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2420. Optical and Dig Standards and Measuring System. The scratch scattering phenomenon study has been completed. The study recommended a scratch profile for the standards. The scratch standards were manufactured in accordance with MBS proposed scratch profile. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2603. Provide Auto Sphericity Interferometer for Test Lens Surfaces. The technical work has been completed. The final report is available. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2631. Critical Electromagnetic Inspection Problems Within the Army. The evaluation of the eddy current instrumentation was started. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2803. Automatic Measurement of Strength and Oxide Limiting Flaws in Ceramic Turbines. The objective of this effort was to develop the capability to correlate pore structure to strength limiting flaws. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2804. Binary Munitions Mechanical Rupture Properties Test. Prototype apparatus has been completed. The shuttle valve spool has been redesigned providing superior force balancing characteristics and easing manufacturing. Final drawings and instrumentation manual are in process. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2811. M42/M46 Magnetic Flux Leakage Inspection. The MFL inspection system design and standards have been reviewed. The fabrication of system is in process. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2815. Cannon Tube Automated Chrome Plate Thickness Measurement. The specification for the development and fabrication of the custom interface had been prepared and sent to procurement for review. Changes were proposed and the specification was revised. It is ready for solicitation. The fixture design is complete. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2817. Fiber Optic Cable Assemblies Test Criteria Development. After evaluating the proposal, it was concluded that the funds that were available were insufficient. AMMRC was advised of this situation. Additional funds were made available. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2828. Composite Motor Cases Acoustic Emission Proof Test Damage Evaluated. This project has been completed. The technical report has been submitted. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2829. Detector Dewar Microphics Production Test Set and Procedures. The final design of this test station is complete. Orders have been placed for much of the hardware (vibrational and electronics) under the IPE expansion contract. Test fixture design is still in progress. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2858. Stress Reading Transducer for Large Composite Components. The test fixture has been completed. A luna-pro photometer has been acquired. For more information, contact Paul Rolston, AMMRC, (617) 923-5466.

Project 6350-2943. Depleted Uranium KE Penetrators Ultrasonic Inspection Procedures. The sonic unit and the M774 S/N 735 heat treated standards were returned to Battelle Pacific Northwest Laboratories. In review the progress of the project, it was determined that the measurement of offset transducer distance need

New Approach to High Reliability

Leadless Components for Printed Wiring Boards

PAUL WANKO is a Project Manager in the Manufacturing Technology Division, System Engineering Directorate of the Army Missile Laboratory, U.S. Army Missile Command. After graduation from Pennsylvania State University with an Associate degree in Engineering, he came to Redstone Arsenal while working for the Navigation Division of the Bendix Corporation as a field representative on the PERSHING Missile System. He began working for the Guidance and Control Directorate of the Army Missile Command in 1965 as a packaging designer and since has contributed to the designs of many Army missiles and launches. In 1970 he headed up the Hybrid Microelectronics Design Group in support of the new Hybrid Laboratory at the Missile Command. A few of his hybrid microelectronic designs are Range Safety devices, Detector Preamplifiers and Missile Auto Pilot. He is currently managing several MM&T projects and is responsible for the progress and reporting of these projects. He is a member of International Society for Microelectronics, Huntsville, AL chapter.

Higher reliability of printed wiring boards was achieved by the U.S. Army Missile Command when the printed wiring board was fabricated from a laminate whose coefficient of expansion approximates that of a leadless chip carrier and which then was bonded to a thermal mounting plate which constrains thermal expansion. This stabilized system reduced the number of fractures of the solder joints from fatigue when the board was thermally cycled.

Under direction of the System Engineering and Production Directorate, the ground systems group of Hughes Aircraft Company conducted a program which was directed toward the establishment of low cost/reliable manufacturing technology for the direct attachment of leadless hermetic chip carrier packages to printed wiring boards.

Leadless components are presently being used in the electronics industry to increase component density, improve electrical performance, and reduce assembly costs. When the leadless chip carrier is directly attached to the printed wiring board solder acts as both the electrical and mechanical connection. Since leadless chip carriers are devoid of leads, any mismatch of coefficients of thermal expansions between the printed wiring board and leadless chip carrier will result in stress on the solder joints during thermal cycling and subsequent failure of the solder joint from fatigue after a certain number of cycles.

Existing co-fired ceramic multilayer technology circumvents the above problem by utilizing an alumina substrate whose coefficient of thermal expansion matches that of the chip carrier. While the use of the ceramic substrate offers reliable surface mounting of leadless chip carriers, the

NOTE: This manufacturing technology project that was conducted by Hughes Aircraft Company was funded by the U.S. Army Missile Command under the overall direction of the U.S. Army Manufacturing Technology Program office of the U.S. Army Materiel Command (AMC). The MICOM Point of Contact for more information is Mr. Paul Wanko, (205) 876-7079.

disadvantages are high cost, size restriction, weight, high dielectric constant, and availability of suppliers.

Present-day printed wiring board materials of either epoxy/glass or polyimide/glass are not thermally compatible with leadless chip carriers. Differences between their coefficients of thermal expansion and the leadless chip carrier cause stresses in the solder joints when subjected to thermal cycling over larger temperature extremes. Proposed methods for reducing the coefficient of thermal expansion mismatch are leaded carriers, socketing of leadless chip carriers, thick leadless chip carrier/printed wiring board solder joints, which significantly reduce the level of stresses in the joint, require additional operations while creating processing problems. The use of a low-expansion organic material, such as a polyimide/Kevlar, solves the coefficient of thermal expansion mismatch and greatly reduces or eliminates solder joint cracking.

Primary and Secondary Criteria Established

The primary objective of this program was to develop the manufacturing techniques/processes for production of printed wiring boards utilizing leadless components. The following requirements were established to meet this objective:

Primary Criteria

- Material Properties—Materials must have properties conductive to existing PWB technology and capable where necessary of surviving the various processing environments

- Fatigue Life of Solder Joints—The selected materials and processes must reduce the stress level on the solder joint thereby enhancing its fatigue life in thermal cycling..

- Cost—The system cost must be equal to or less than that for printed wiring boards utilizing through hole mounted components.

- Reliability—Printed wiring assemblies populated with leadless components must be capable of maintaining electrical and mechanical connections under the required environmental conditions.

Secondary Criteria

- Fabrication—Printed wiring boards must be capable of being fabricated by processes considered standard in the printed wiring board industry.

- Assembly—Assembly of leadless components must be adaptable to automated high volume production methods.

- Repairability—Removal and replacement of leadless components must be readily accomplished without degrading the printed wiring board and electrical performance of the component.

Material Evaluation and Selection

Material evaluation and selection (Phase I) commenced with a cursory industry/literature search with a list of the possible materials for the packaging/interconnection substrate materials and their assembly. The survey comprised a review of the literature in the field of leadless chip carrier technology with specific emphasis on the matching of the thermal coefficients of expansion of the chip carrier and the printed wiring board. The principal data sources for bibliographic material are listed in Table 1.

- Defense Document Center
- Engineering Index
- Institute of Printed Circuits
- National Technical Information Service
- Electronics Industry Association
- California Circuits Association

Table 1

The information gathered during this task included sources of laminates, solder pastes, thermal conductive compounds, chip carriers, adhesives, and thermal mounting plate materials. This information was used to establish a screening program for the materials for evaluation in Phase I.

Also, principal manufacturers of military and industrial electronic assemblies were surveyed at the beginning of this program to identify those firms utilizing printed wiring boards with directly attached leadless chip carriers.

All materials were reviewed from the standpoint of manufacturing, processing, and commercial availability. The preliminary review focused on modified polyimide/Kevlar as the substrate material. Solder pastes were characterized for their alloy content and ability to produce a dense, concise repeatable solder print. Thermal mounting plate adhesives were evaluated for their ease of processing and ability to withstand adverse environments. Thermal

undercoats were screened primarily for ease of application and removal and thermal conductivity. The thermal management addressed the efficiency of various conduction modes in dissipating heat from the chip carrier.

Evaluation and Selection of Printed Wiring Board Materials

Increasing demands for very high-speed information processing and large-scale integration require an increase in package density conducive to the use of leadless chip carriers on printed wiring boards. Since the leadless chip carrier is directly attached to the printed wiring board by soldering and there is an absence of leads on the package, the thermal mismatch between them incudes a high stress level in the solder joint, thereby resulting in a reduced fatigue life during thermal cycling. An increase in the number of cycles to failure is directly related to

(1) A decrease in the difference in coefficients of thermal expansion between the printed wiring board and leadless chip carrier
(2) An increase in the thickness of the solder layer
(3) A decrease in the range of thermal cycling
(4) A decrease in chip size.

The selection of a compatible interconnection system ultimately is related to a reduction in the total change of strain induced in the solder joint by thermal cycling. Figure 1 shows a simplified dimensional analysis of the effect of temperature on the solder joint.

Basic Approaches Proposed by Industry

Primary emphasis on industry has been placed on extending fatigue life by minimizing the thermal coefficient of expansion difference between leadless chip carrier and printed wiring board. The basic approaches used to improve the reliability of the solder joints include the constrained expansion method, controlled method, and complicant method.

- **Constrained Expansion Method**

The constrained thermal mounting plate approach is a method inclusive of a low-expansion substrate design either as a bond material for the substrate frame (Figure 2) or as a composite to reduce substrate expansion (Figure 3). In the plan view of of Figure 2, conventional printed wiring boards fabricated and bonded with a rigid adhesive to a low coefficient of thermal expansion metal core as copper clad Invar or copper clad molybdenum will be controlled by the metal core in the X and Y axes. However, there are several design considerations for this type of construction that must be followed. If not, the effectiveness of the constraint would be greatly reduced. These considerations are:

(1) The thickness ratio of the low expansion metal to the PWB and

(2) The thickness of the bond line. The thickness ratio between the metal and printed wiring board is derived from the thermal coefficient of expansions and the elastic modulus of the materials. The thickness of the bond line should be kept to a minimum for a maximum restraining effect.

In Figure 3 the thermal coefficient of expansion of the composite can be controlled through the use of a low expansion metal layer such as copper clad Invar or graphite laminated between the high-expansion substrate printed wiring board material. In such composites, the overall thermal coefficient of expansion can be controlled to the

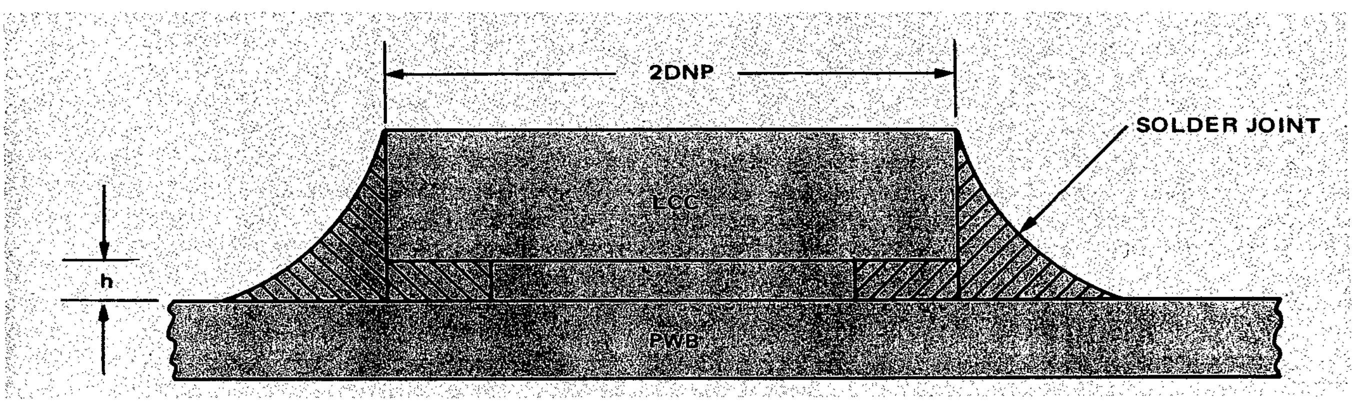


Figure 1

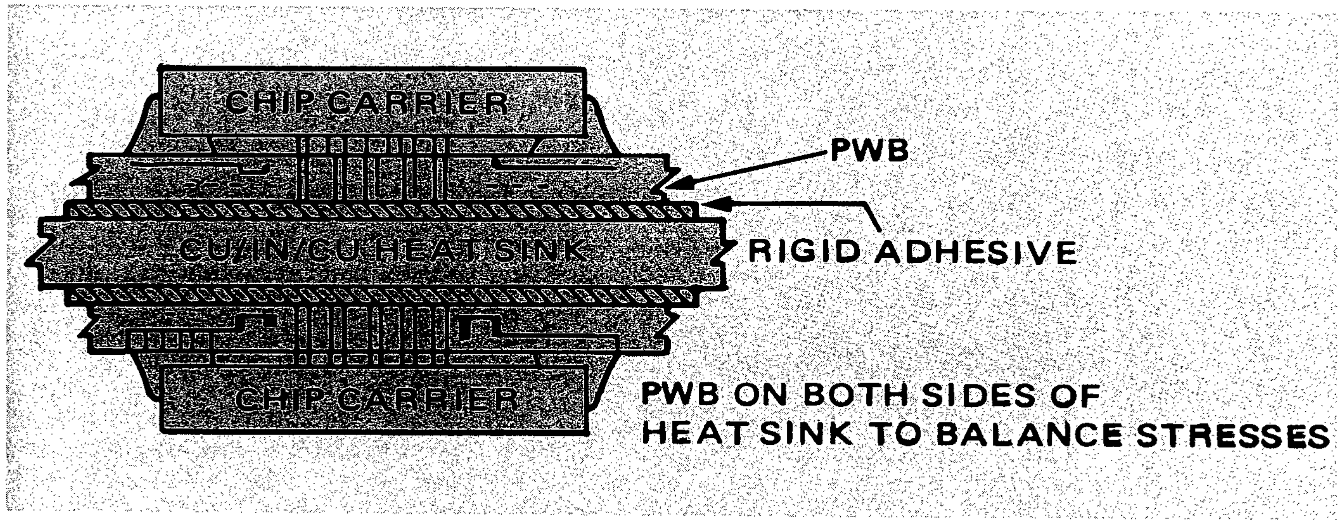


Figure 2. Constrained Expansion Design Utilizing Low Expansion Materials as Substrate Frame Bonds

level of that of the leadless chip carrier. Other derived benefits of the composite substrate are:

(1) The metal foils can serve as power and ground planes in the circuitry and

(2) The thermal properties of the composite substrate can be improved because of the presence of the metal or graphite layers. The graphite is advantageous as a low weight/high thermal conductivity internal layer of the printed wiring board. However potential problems arise from its inherent high electrical conductivity and the possibility of misregistration in fabrication of large sizes.

- **Controlled Method**

The simplest physical approach is a design wherein a low expansion organic or inorganic system (as shown in Figures 4 and 5) with an inherent closer matching thermal coefficient of expansion is used as the substrate for the leadless chip carrier. This material system would directly extend the fatigue life of the solder joints during thermal cycling. Candidate materials for the organic system are Kevlar epoxy or Kevlar polyimide, polyimide-glass, and polyimide-quartz. Co-fired ceramic, ceramic thick film, and porcelainized ceramic represent he inorganic systems.

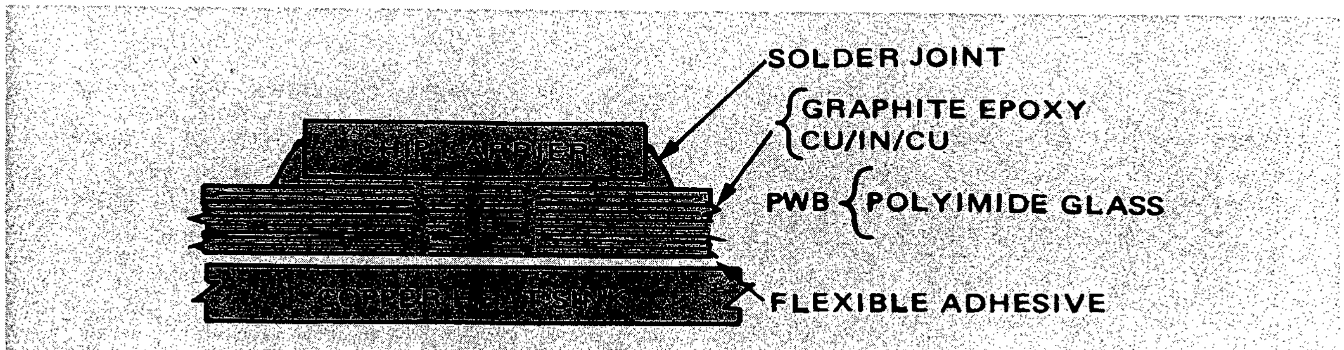


Figure 3. Constrained Expansion Design With Low Expansion Materials in the PWB

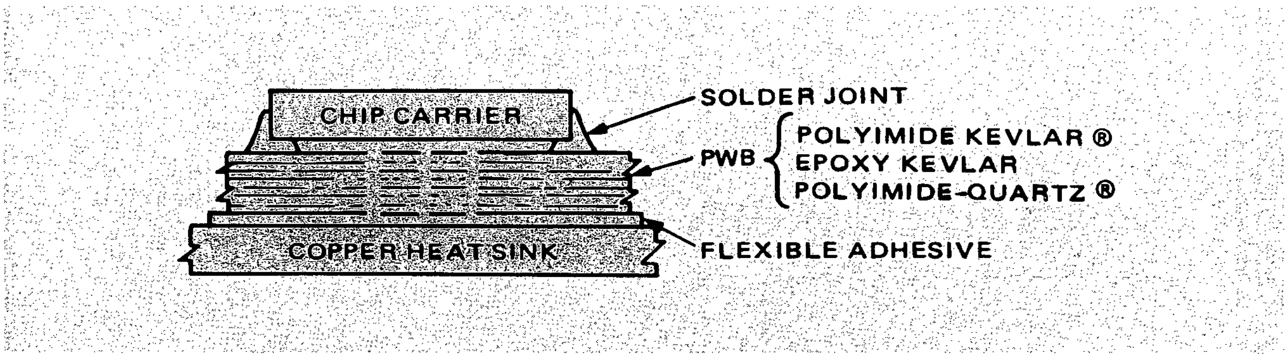


Figure 4. Organic Controlled Expansion

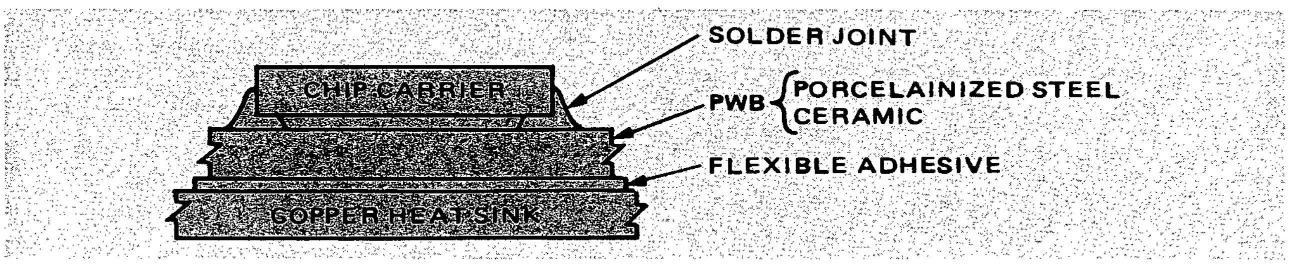


Figure 5. Ceramic or Porcelainized Steel
(Controlled Expansion)

● **Compliant Method**

This design compensates for differences in thermal coefficient of expansion between the printed wiring boards and leadless chip carrier by:

(1) Distributing the net strain and strain energy over a larger area through flexibility in the solder joint (Figure 6)

(2) Reducing differences in applied solder strains through the placement of a compliant layer between the footprint of the solder joint and the printed wiring board (Figure 7) and

(3) Transmitting the strain of the thermal coefficient of expansion mismatch directly from the leadless chip carrier to the printed wiring board by placing a thermally conductive compound into the air gap beneath the leadless chip carrier (Figure 8).

Of these methods, those which appear most promising are the compliant layer substrates which utilize the principle of reducing the equivalent elastic strain by interfacing the component pads and conductor pattern and substrate with an elastomeric coating. Several patented systems utilizing this technique are now available on the market. Data on the reliability of this system is scarce, although it is known that the strain on the solder joints of the leadless chip carrier is considerably reduced by the compliant layer. A possible problem with plated through holes could arise from the high Z-axis expansion.

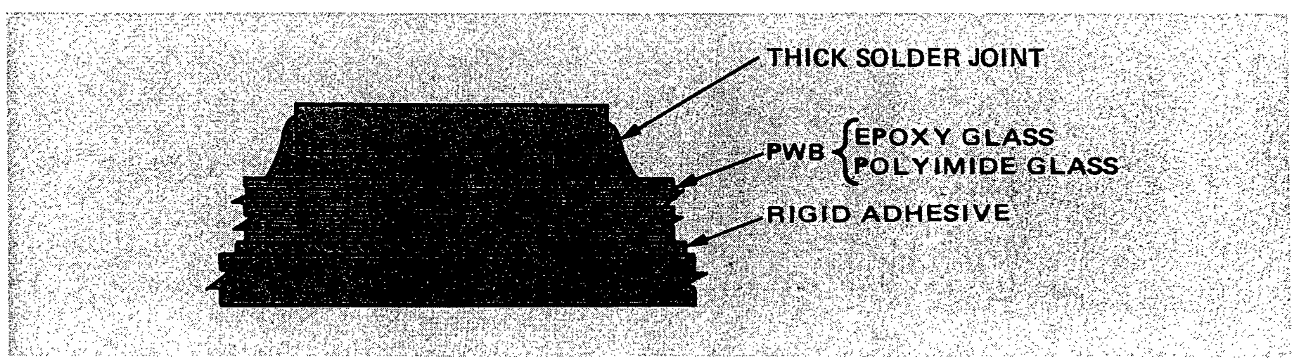


Figure 6. Unconstrained Joint Configuration

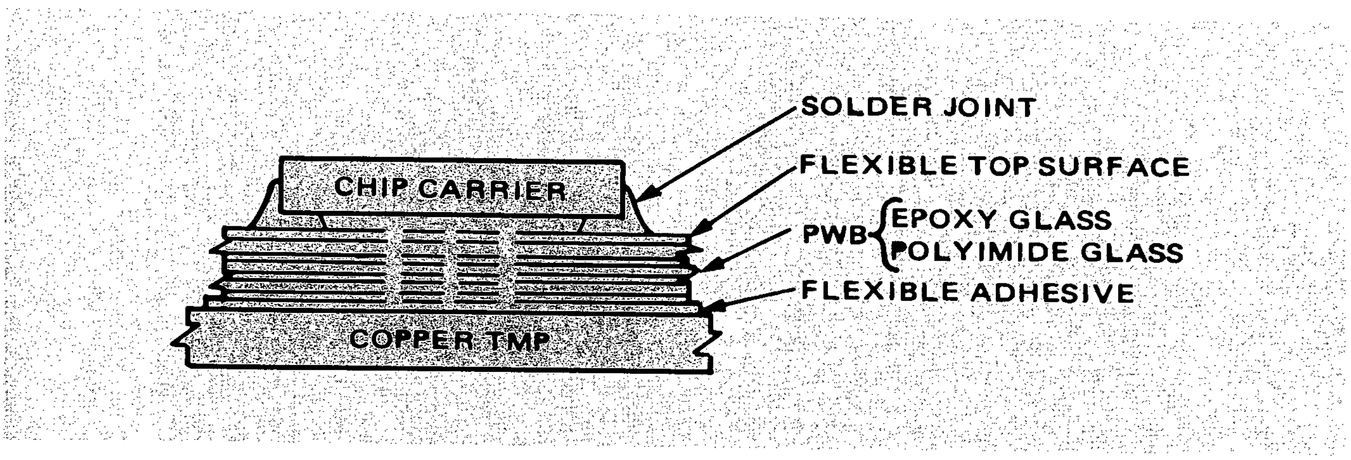


Figure 7. Flexible Surface Layers

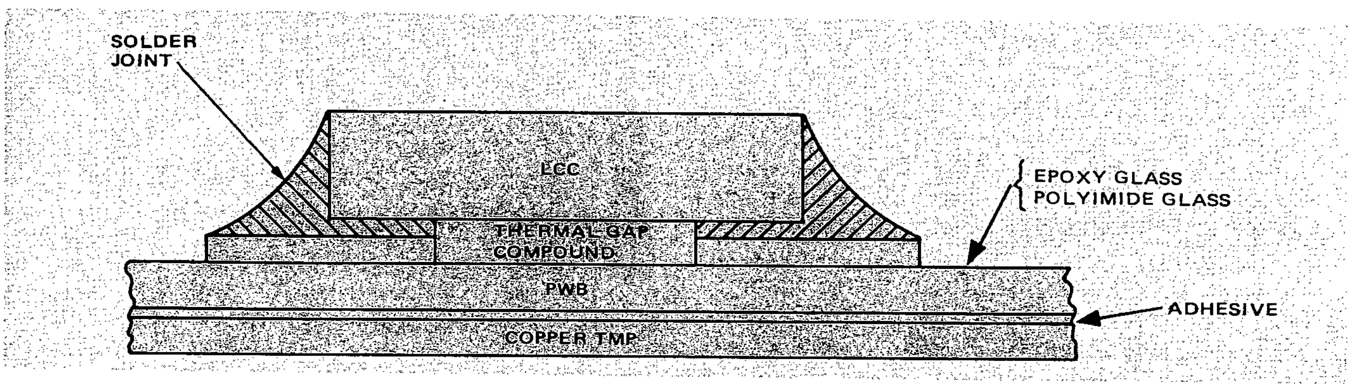


Figure 8. Thermal Compound Distributes Stress from TCE Mismatch

Preliminary Conclusions

After completion of this phase of the work, several conclusions were reached:

- Kevlar reinforced polyimide was selected for use as printed wiring board material because its thermal coefficient matches closely with that of the ceramic leadless chip carrier. The physical and electrical properties of the material have been investigated and were found to be acceptable for military application.

- Solder pastes from a number of manufacturers were evaluated in percent solid content, oxidation resistance, and screenability tests. Additionally, the particle shape and size, activity of the flux, and flux content of the pastes were evaluated. For consistency, one solder paste was used throughout the program.

- Adhesives for bonding printed wiring board to thermal mounting plate were selected and evaluated. Bonding printed wiring board to thermal mounting plate prior to soldering was found impractical because of the interference in injecting the thermal undercoat. The adhesive used was selected because of its low curing temperature, ease of application and removal of the thermal mounting plate from the printed wiring board, high thermal conductivity, and the ability of reducing warpage in the bonded

- An alumina filled epoxy, was selected for the thermal undercoat because of its low viscosity and high thermal conductivity. Low viscosity was necessary for injecting the thermal undercoat into the gap between the leadless chip carrier and the printed wiring board.

Thermal analysis was performed for the printed wiring board/thermal mounting plate assembly using computer modeling. A three dimensional resistive network model

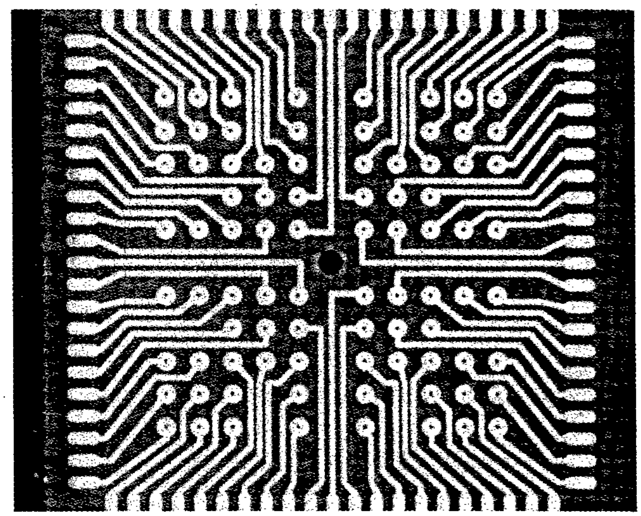
was developed to simulate the thermal characteristics and response of the circuit cards. In addition to the computerized thermal analysis, actual thermal measurements were made on the circuit cards to provide empirical data for checking the computer results. The results of the theoretically and empirically obtained data correlated in most cases. The results showed that the alumina-filled epoxy reduces the thermal resistance between the leadless chip carrier and the printed wiring board in most cases. The effect of filling the vias with solder was the greates for the small leadless chip carriers. For the large leadless chip carriers, the improvement was very small over the non-filled vias.

Process Development

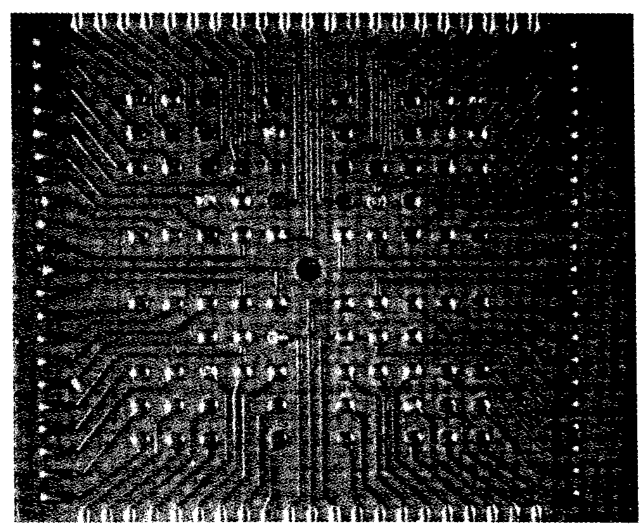
Process development (Phase II) concentrated on determining the optimum methods for attaching leadless components to rigid and rigid-flex fine line circuits utilizing the materials selected in Phase I. Test boards were fabricated from both polyimide/glass and modified polyimide/Kevlar with high density circuit designs. Printing parameters for solder pastes from Phase I were optimized with both manual and automated screen printers. Procedures for (1) semi-automatic tinning, (2) removal and replacement of leadless components, and (3) application of the thermal undercoat were developed. Attachment of the leadless components to the printed wiring board by conveyorized belt furnace reflow and vapor phase condensation soldering was evaluated. Cleaning of the soldered printed wiring assemblies (printed wiring assemblies) by standard operation and with common industry solvents was examined. Procedures for bonding the printed wiring assemblies to thermal mounting plates were established using materials selected in Phase I.

Methods of filling the vias as wave soldering or plating and fusing were examined as their repeatability and process feasibility. It was found that extremely rigid control of wave soldering parameters was necessary to ensure completely filled vias. Tinning of leadless chip carriers with solder by static and wave soldering methods was evaluated by visual inspection for uniform coverage of castellations of the leadless chip carrier and by scanning electron microscope for gold contamination of the solder. Solder prints were deposited on the footprints of the printed wiring board with a manual screen printer and inspected for pattern definition (Figure 9). Both vapor phase condensation and conveyorized belt furnace soldering were assessed as to their effect on substrate materials and the ability to yield solder joints (Figures 10 and 11).

Manual placement of leadless chip carriers on substrates was found to be labor intensive and fatiguing to personnel. Automatic pick and place equipment was assessed as to their rate of placement, cost, and maintenance (Figure 12). Adhesives for bonding the printed



Prior to Fusing (3X)



After Fusing (3X)

Figure 9.

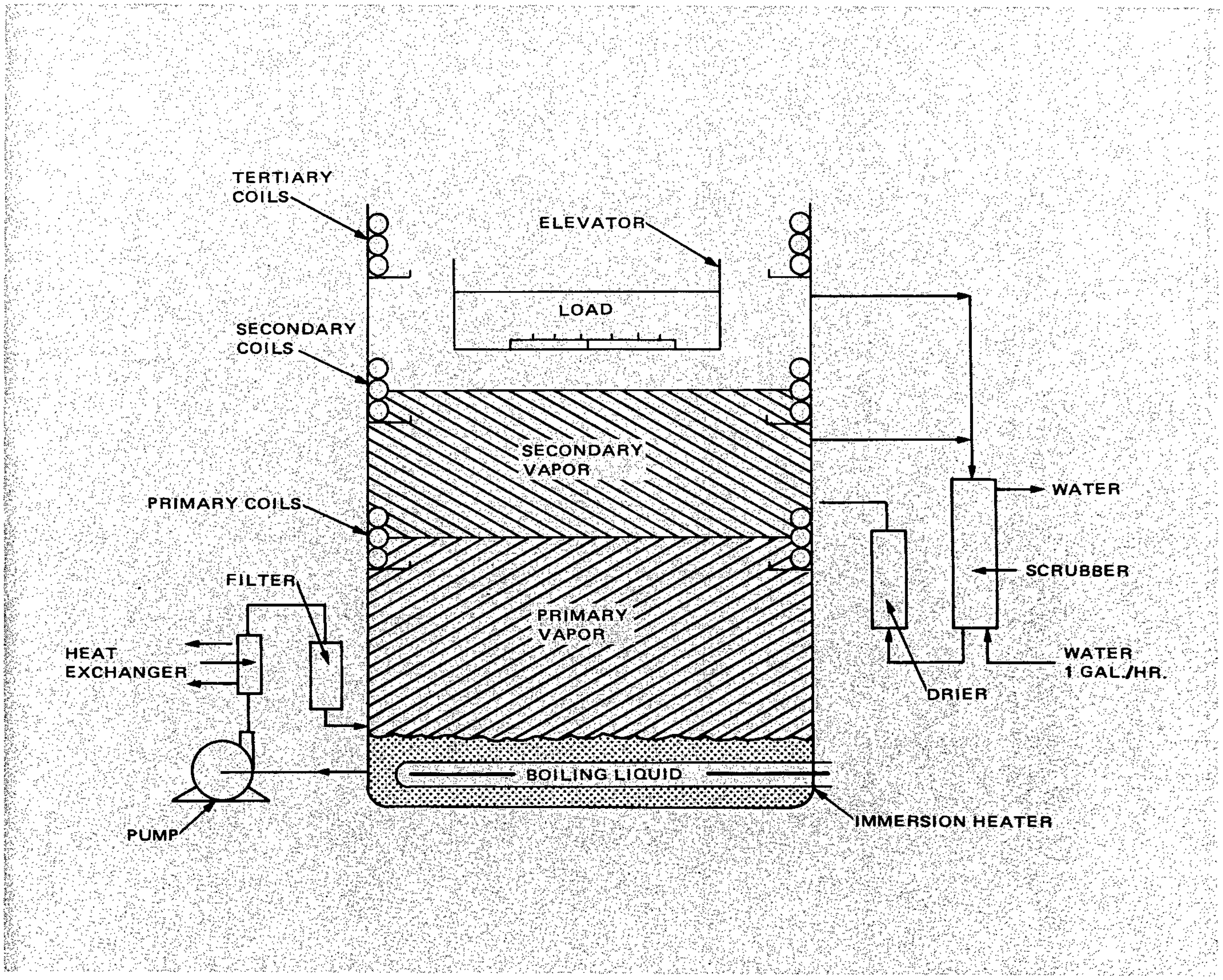


Figure 10

wiring board to the thermal mounting plate were evaluated for their resistance to adverse environments and ease of application and removal from the thermal mounting plate. A method of applying the thermal undercoat was developed which includes the use of a specific injection hole size and semiautomatic equipment. Additionally, a procedure for removal and replacement of chip carriers and the undercoat was developed. Cleaning solvents wee utilized which would solvate the residual flux thereby yielding an assembly conforming to the cleanliness requirements of MIL-P-28809. Board cleanliness was determined prior to and after attachment of the leadless chip carriers by employing an Omega Meter. Conformal coatings meeting the requirements of MIL-I-46058 were assessed as to their environmental resistance and ease of application and rework.

Environmental Testing

Environmental tests were conducted on a significant number of printed wiring boards assembled with leadless chip carriers. Tests were performed for two conditioins—i.e., with and without a thermal undercoat. Humidity, vibration, and thermal cycling tests were conducted in accordance with MIL-STD-202E, whereas acceleration and mechanical shock testing conformed to MIL-STD-883, Condition E. The test levels in each test were selected to provide a damage potential well above that resulting from a typical qualification test. Verification of the ability of the assemblies to meet the test requirements was effected by visual and microscopic examination of the printed wiring boards after each increment of environmental test. Damage made to component packages was noted and identified. Since the initial packages tested for mechanical shock failed, the severity level was reduced until package survival was obtained on consecutive test specimens.

Visual inspections were performed with a light microscope to magnify the leadless chip carrier, solder joints, and other areas of the assemblies. These inspections were performed on each leadless chip carrier and each joint during each inspection period.

This study included five different sizes of leadless chip carriers chosen to provide a representative spectrum of those commonly available, as shown in Figure 13.

Four different printed wiring board patterns were used

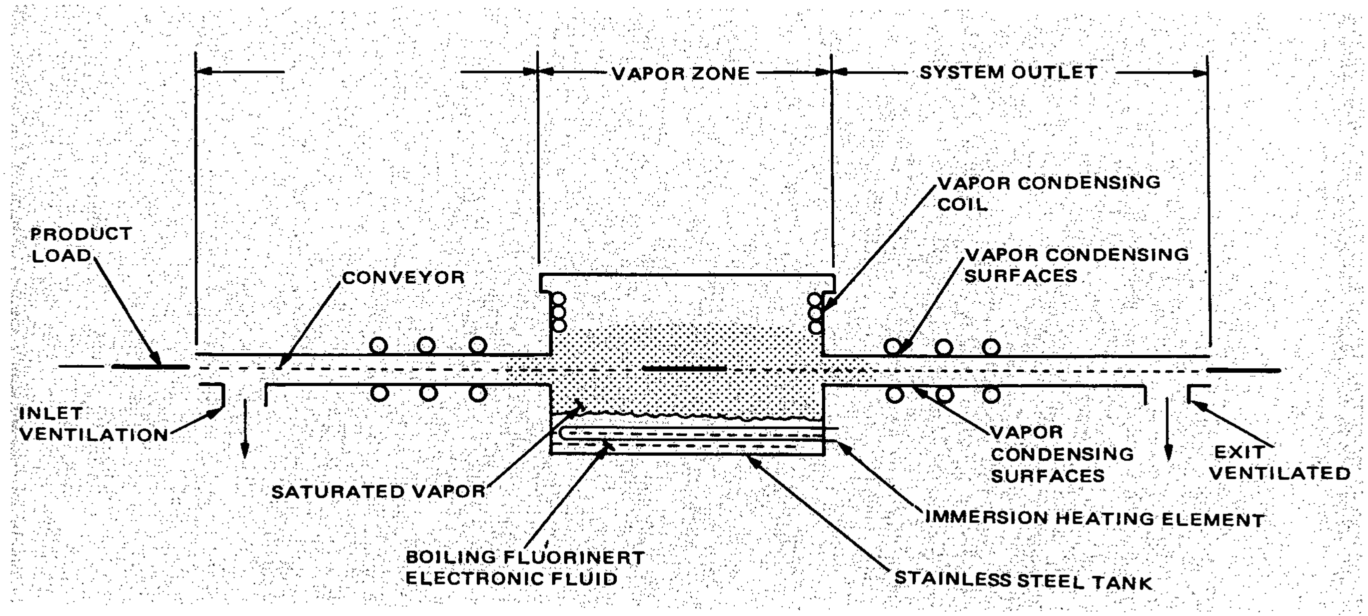


Figure 11

for the test assemblies. Previous investigations at Hughes established the pad sizes, thermal via dimensions, and other details as significant design considerations for the manufacture of reliable leadless chip carrier assemblies. Only processes developed for large-scale manufacturing were used to fabricate these assemblies.

These assemblies were typical of those suggested for military hardware. Close packing of leadless chip carriers allowed a maximum usage of materials and space and provided a worst case condition for these environmental tests because of the greater difficulty of conformal coating assemblies prior to humidity testing, greater rigidity of the printed wiring assembly during thermal cycling, and greater mass of the printed wiring assembly, which causes greater deflection during vibration.

The samples prepared for shock and acceleration testing differed only slightly from those prepared for the thermal cycling, vibration, and humidity testing. The available shock and acceleration test equipment limited the size of these test samples. Therefore, leadless chip carriers were assembled onto printed wiring boards identical to those used for thermal cycling, vibration, and humidity testing. Subsequently, sections were cut from these assemblies for shock or acceleration testing.

All printed wiring assemblies, prepared according to those processes identified in Phase II, were tested on both modified polyimide/Kevlar printed wiring boards and polyimide/glass printed wiring boards mounted on standard 0.050-inch-thick copper. The Kevlar printed wiring board material matches the coefficient of thermal expansion of the leadless chip carrier, the polyimide/glass material was used as the control.

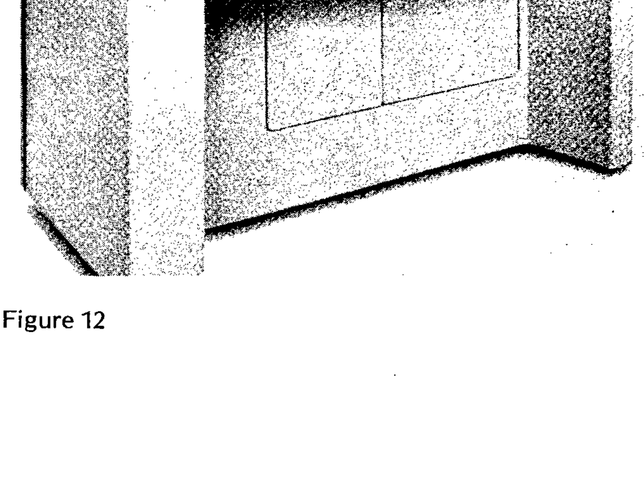


Figure 12

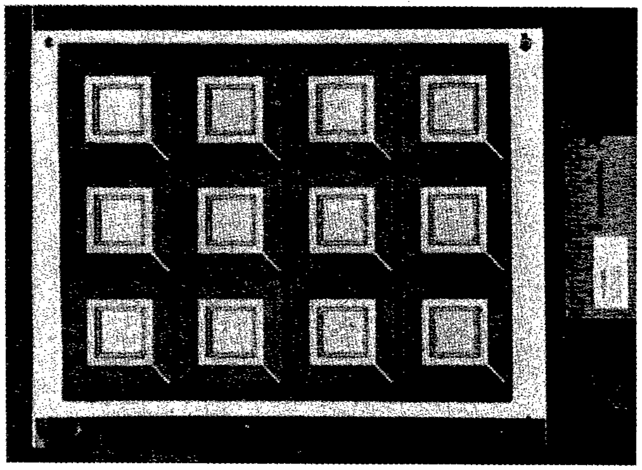


Figure 13

All five sizes of leadless chip carriers, undercoated and mounted on both modified polyimide/Kevlar printed wiring boards and polyimide/glass printed wiring boards bonded to copper thermal mounting plates, were tested in humidity, vibration, shock, acceleration, and thermal cycling. Thermal undercoat was injected beneath the leadless chip carrier to fill a circular radius tangent to the leadless chip carrier for heat dissipation.

In addition, several tests were performed to ascertain the effects of processing variables on package reliability. These leadless chip carriers were the most sensitive to environmental effects and therefore amplified the effects of material and process variations. These tests evaluated the effects of

(1) Reinforcing the joints with a rigid epoxy
(2) Eliminating the thermal undercoat and
(3) Using a copper-clad Invar thermal mounting plate on the survivability of leadless chip carriers attached to polyimide/glass printed wiring boards during thermal cycling. The leadless chip carriers without a thermal undercoat were also tested in vibration, shock, and acceleration for polyimide/glass printed wiring boards mounted on copper thermal mounting plates to determine whether the undercoat significantly enhanced package directly reliability. For the same reason, leadless chip carriers without the thermal undercoat and mounted on modified polyimide/Kevlar printed wiring boards bonded to copper thermal mounting plates were tested in acceleration.

Data from the environmental tests were analyzed to estimate the reliability of the mechanical and electrical interconnections under the specified environmental conditions. The data analysis presented the observed failure rate compared to the increments of damage potential for each environment.

Environmental Testing Conclusions

Printed wiring assemblies fabricated from the materials selected in Phase I and assembled in accordance with the assembly processes developed in Phase II of the program were tested in humidity, vibration, shock, acceleration, and thermal cycling. The results indicated that printed wiring assemblies subjected to humidity test showed no corrosion or any other form of degradation. Neither the printed wiring board, thermal mounting plate, adhesive, conformal coat, or coating was affected by the humidity testing. In vibration testing, all the printed wiring assemblies, with one exception, passed the severe vibration test requirements. The exception was found in the leadless chip carriers without the undercoat, wherein those showed a sign of solder joint cracking.

The results of shock testing indicated that the thermal undercoat apparently enhanced the survival level of the packages, as indicated by the test performed on the leadless chip carriers without an undercoat in the space between the printed wiring board and leadless chip carrier.

The leadless chip carriers mounted on polyimide/glass or modified polyimide/Kevlar printed wiring assemblies sustained no damage from an acceleration test. Greater G levels cracked leadless chip carriers in the same manner as mechanical shock, and failures occurred during acceleration perpendicular to the plane of the printed wiring boards. No other damage or degradation of the assemblies was detected after testing.

Modified polyimide/Kevlar printed wiring boards attached to copper clad Invar thermal mounting plates provided the greatest reliability for thermal cycling tests. Both undercoated and nonundercoated leadless chip carriers mounted on these assemblies survived over 400 thermal cycles without any solder joint cracking. The packages directly attached to modified polyimide/Kevlar printed wiring boards mounted on copper thermal mounting plates survived 600 cycles and 1000 cycles without solder joint cracking, respectively. It was believed that the life of the solder joints of these packages could be extended if the thermal mounting plate were copper clad Invar. Because packages fractured when mounted on the modified polyimide/Kevlar—copper thermal mounting plates assemblies in the first 20 cycles of testing, no additional tests were performed with these packages. Again,

it was believed that the life of the solder joints of these packages could be extended beyond the 400 cycles obtained for the larger packages if copper clad Invar thermal mounting plate were used.

Most of the leadless chip carriers of polyimide/glass printed wiring boards bonded on copper assemblies, experienced solder joint cracking in less than 100 thermal cycles and only one survived 200 cycles. Additional tests with leadless chip carriers using polyimide/glass printed wiring boards and techniques to extend solder joint life were found either unacceptable for manufacturing or ineffective.

Chip discrete components were subjected to thermal cycling. Barium titanate chip capacitors fractured in the ceramic body after testing. No physical or electrical damages were detected in the tantalum chip capacitors and chip resistors.

Modified polyimide/Kevlar exhibited early resin cracking in the thermal cycles. However, resin cracking did not lead to the degradation of the board. The use of Kevlar paper greatly reduced the amount of resin cracking in the laminate. The results for the paper reinforced material, however, are incomplete at this time.

Barrel cracking was evidenced in both the modified polyimide/Kevlar and polyimide/glass boards after the thermal cycling. However, in most cases, the cracks failed to traverse the plating in the plated through holes, which were more prone to barrel cracking for the Kevlar reinforced boards than the glass reinforced ones because of the slightly greater Z-axis expansion of the Kevlar.

Trade-Off Analysis Conducted

The trade-off analysis encompassed the trade-offs and changes involved in the utilization of leadless chip carriers and other leadless components on printed wiring boards. The objectives of the trade-off analysis were:

- Establish the criteria for achieving a highly reliable interconnection system for leadless chip carriers for use in diverse environments and military applications.
- Maximize the highly integrated circuit density inherently associated with printed wiring boards populated with leadless chip carriers.
- Minimize the impact of leadless chip carrier technology on design activities and manufacturing operations.

Specific areas addressed included:

- **Component Packaging**
  - Leadless vs Leaded Chip Carriers
  - Package Materials and Construction
  - Functional Density
  - Electrical Performance
  - Thermal Characteristics
  - Weight
  - Size
  - Cost
  - Repairability
  - Testability
  - Reliability
  - Standardization
  - Availability
- **Interconnection**
  - Package/System/Thermal Mounting Plate Concepts
  - package/Leadless Chip Carrier Interconnection Substrate Materials
  - Thermal Mounting Plates
  - Thermal Management
- **Manufacturing**
  - Assembly
    - Solder
    - Plating and Preparation of Printed Wiring Boards
    - Application of Solder Pastes
    - Component Placement
    - Soldering
    - Cleaning—Flux Removal
    - Application of Thermal Undercoat
    - Attachment Sequence for Leadless Chip Carriers
    - Conformal Coating
    - Removal and Replacement of Components
  - Inspection
    - Visual
  - Reliability of Leadless Chip Carrier Populated Assemblies

Costs play a big part in this analysis and deserve specific attention. Costs for assemblies populated with surface mounted leadless components depend on various factors. Generally cost reductions are realized through a reduction in the number of printed wiring board assemblies required. Individual assemblies will be more complex because of their higher density.

Prime candidates for leadless chip carriers usage are those assesmblies with high density and conventional components. Usually this type of assembly presents difficulties in manual operations because its complexity leads to human errors. Robotic placement of components is repeatable and prone to very few errors.

A fairly simple assembly requiring a few smaller packages will cost more in the conversion of through hole mounted components to leadless chip carriers. The volume also plays a significant role in the feasibility of the decision to change to leadless components. The prime overriding factor for deciding on converting double inline packages, e.g., to leadless chip carriers on an assembly is the certainty that the production cost for a leadless chip carrier will decrease in future years. As with most emerging technologies, the high cost of leadless chip carriers presently is a temporary condition. Price parity is expected to be attained in the near future.

Low density circuits with low labor are unlikely candidates for leadless chip carriers usage unless high reliability and smaller size are weighting factors wherein leadless chip carriers should be only used if a large production run dictates their use.

Economic considerations for the use of leadless components include the component availability and cost. Both considerations must be assembled into a cost factor related to the cost of inventory and lead time. In many instances, the initial cost of a component is minimal compared to the true "assembled" cost. Availability of components significantly adds to the cost of assemblies populated with leadless chip carriers. However, the availablity follows a diminishing cost curve because of the increase in availability of parts with time.

The future of direct attachment (surface mounting) of leadless chip carriers depends greatly on the high volume assembly equipment and machinery. Such equipment is sophisticated and expensive with manufacturers producing equipment with improved capabilities and of lower cost every year. The significant point for consideration is the production rate in units per hour since higher rates reduce the cost per part.

The breakeven point for the leadless chip carrier technology is quite evasive as is true for any new technology. Factors of labor content, size, density of circuits, reliability, environmental service, and volume of printed wiring assemblies should be included in the formula for evaluating the breakeven point. The components of the system for producing a leadless chip carrier populated assembly greatly affects the final cost because direct attachment of leadless chip carriers is a method dominating technology.

A substantial output of the leadless chip carrier technology to date is its potential for substantial reduction in cost because of the following:

- The intrinsic cost of the materials are less. Axial or radial lead passive components are more expensive because they use more material and require additional operations to attach the leads. Leadless carriers have one-fifth the material and require no glass to metal seals.

- High-speed microprocessor controlled pick-and-place equipment are used to attach the leadless chip carriers to boards. The cost of this equipment is a fraction of the dual-in-line insertion equipment. Because leadless chip carriers self align during the solder reflow operation, high-speed placement leadless chip carriers with reasonable accuracy is sufficient to meet manufacturing requirements.

- Because leadless chip carriers are very small, large quantities can be kept in various configurations as on tape, in cartridges, or in matrix holding fixtures. Automatic or semiautomatic high speed loading is possible. In many cases, the high-speed pick-and-place equipment can be designed to handle parts as received from the part manufacturer without any additional handling or component preparation thereby reducing costs.

Design Guide

As part of this work, Hughes also prepared a design guide. Specifically, this guide covers the factors to be considered when directly attaching leadless components to modified polyimide/Kevlar printed wiring boards. Included are the requirements for materials, processes, and assembly. The characteristics of the substrate together with thermal management, inspection, rework, testing, etc. are discussed.

As stated in the guide, the etched foil circuit is the most widely printed circuit for military applications. The etched circuit board consists of a precisely etched circuit pattern adhesively bonded to an insulating base of polyimide glass or modified polyimide/Kevlar and provides a means for the support and interconnection of components to be mounted on the board. The etched board is fabricated with printed wiring on one or both sides.

Multilayer boards used in designs requiring very high packaging density possess three or more layers of printed wiring. Connections between layers on etched boards are achieved by plated-through holes.

Process Demonstrated

The materials and processes from Phases I and II were implemented into a pilot line. The line was designed for a prototype production run of 10 boards of at least 7 x 7 inch multilayer boards to verify the manufacturing process.

Information on procedures commonly associated with the attachment of leadless chip carriers to printed wiring boards was provided by the pilot production run. Flatness of the printed wiring board laminate, screen printing of solder pastes, and vapor phase soldering parameters were confirmed. Practices such as storage conditions of solder pastes and shelf life of screened solder deposits were found to require strict adherence to established requirements.

The pilot production line produced 30 boards populated with leadless chip carriers for delivery to the Missile Command for demonstration and evaluation, of which 20 each were double sided printed wiring boards and 10 each were rigid-flex boards with circuitry on each side interconnected by a plated-through hole.

During this phase of work, a set of 104 slides depicting the procedures and processes on the pilot line and a 10-minute movie film were made and delivered to MICOM.

The pilot line was implemented at the beginning of Phase V. A flow chart of the operation is depicted in Figure 14. Figure 15 follows the flow of the tinned leadless components from incoming storage through the various processes to final inspection.

Multilayer boards and rigid-flex boards were fabricated in a production mode utilizing modified polyimide/Kevlar material in their designs, with a combination of leadless and discrete components on the same multilayer board and on rigid-flex assemblies.

The design for the boards was submitted to and approved by MICOM prior to their fabrication. Double-sided (20 each) and rigid-flex (10 each) assemblies were fabricated over a period of 8 weeks and populated with leadess components.

Principal Conclusions and Recommendations

- **Conclusions**—The principal conclusions reached in this program are summarized in Table 2. It was concluded that optimum fatigue life of thermally cycled solder joints results when leadless chip carriers are directly attached to a modified polyimide/Kevlar substrate mounted on a copper-clad Invar thermal mounting plate. The matching coefficients of expansion of the leadless chip carrier,

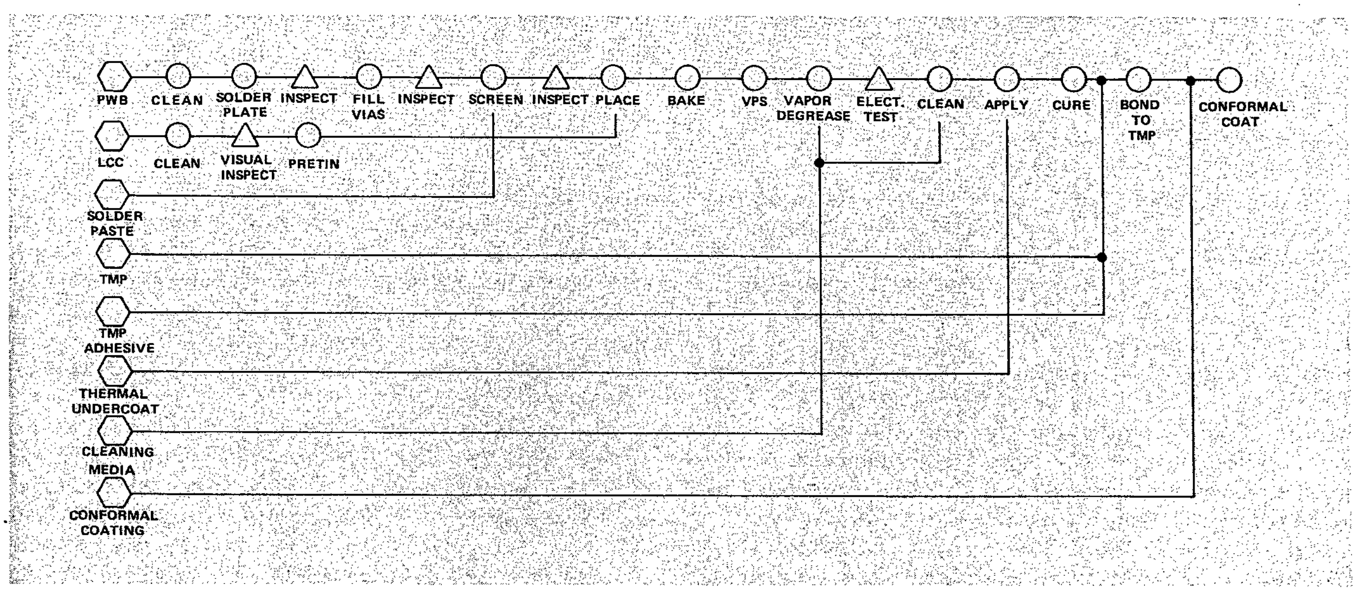


Figure 14

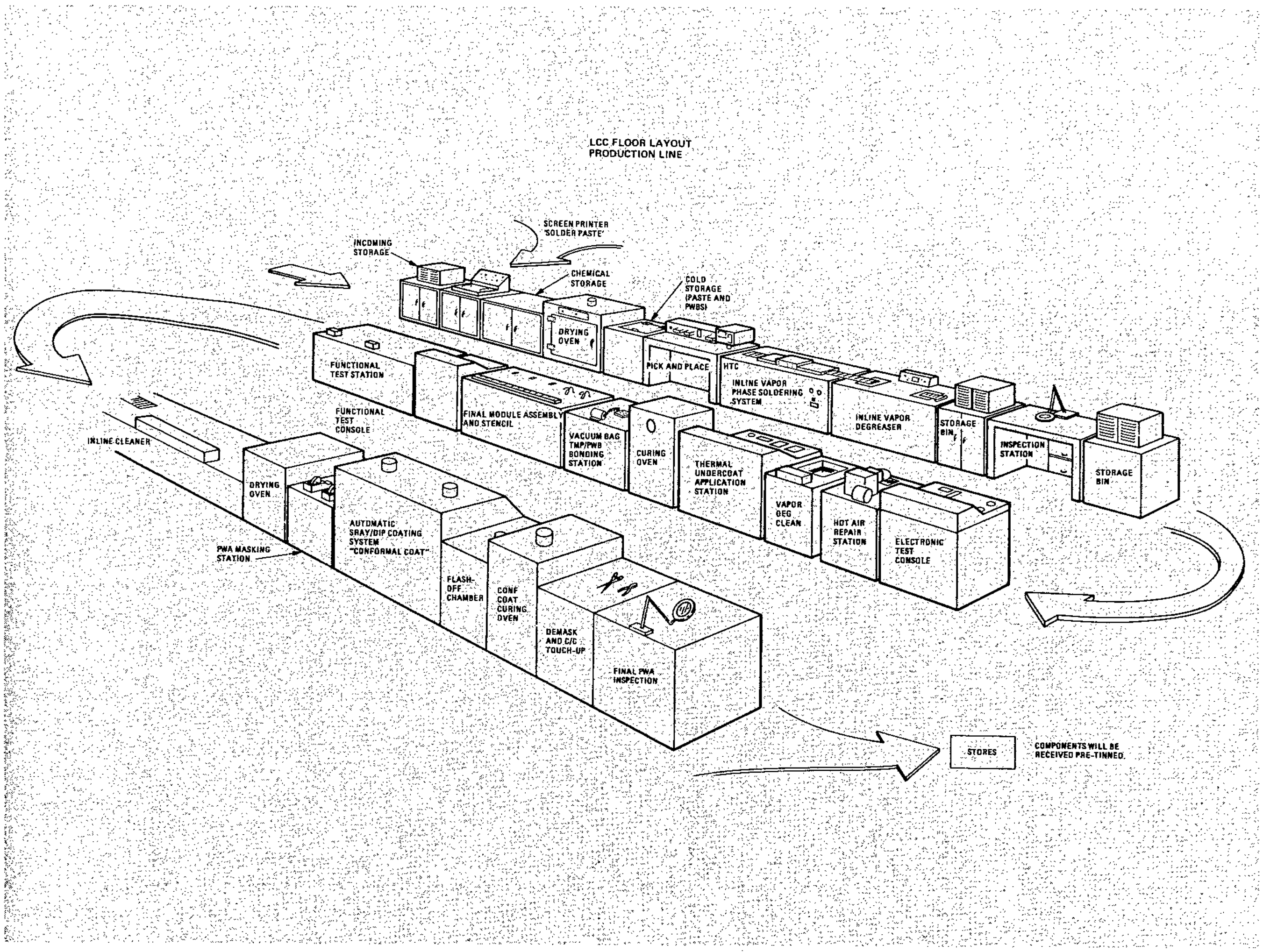


Figure 15

modified polyimide/Kevlar, and copper-clad Invar were directly related to the survival life of the joint.

- Survival life of solder joints is enhanced by closely matching the coefficients of thermal expansion of the leadless chip carrier, printed wiring board, and thermal mounting plate.

- Printed wiring boards of modified polyimide/Kevlar can be readily fabricated with the subtractive process.

- Leadless chip carriers in high density circuits yield lower overall system costs.

Table 2

Modified polyimide/Kevlar printed wiring boards for the attachment of surface-mounted leadless components can be readily fabricated with standard printed wiring board processes utilizing existing standard equipment.

Finally, it was indicated that surface mounting of leadless components should result in a significant reduction in process time because of the automated placement and assembly of the components.

- **Recommendations**—Hughes Aircraft recommendations are summarized in Table 3. To facilitate the use of modified polyimide/Kevlar for military use, the industry and military sectors should revise MIL-P-13949 to allow the use of this material as a substrate. Presently, this specification covers only the epoxy-glass and polyimide-glass materials and no military specification is available for the modified polyimide/Kevlar.

An improved technique for the inspection of the solder joints is needed because existing visual inspection of the large number of joints per leadless chip carrier and the limited access to the solder joint results in early operator fatigue.

Since the fatigue resistance during thermal cycling of the common solder alloys is quite poor, both at ambient and elevated temperatures, consideration should be given to developing an alloy with resistance to grain growth from thermal aging.

- Revise the military specification, MIL-P-13949, for PWB material to allow the use of the low expansitivity modified polyimide/Kevlar.

- Develop better inspection techniques for solder joints.

- Develop solder alloys with improved fatigue resistance.

- Develop fluxless soldering.

- Investigate more efficient modes of thermal management.

Table 3

The small gap between the leadless chip carrier and the substrate does not allow for easy removal or inspection for residual flux. Additionally, a clean periphery around the joints does not assure the absence of flux contamination beneath the body of the chip carrier. To circumvent these conditions, it is recommended that industry develop a soldering technique free of flux (fluxless soldering).

Since heat fluxes rapidly escalate at the chip and package level with a decrease in hue width and an increase in gate counts, an assessment of the thermal control strategies is necessary. Consideration should be given to metal core boards, flow-through modules, and heat pipes. Metal core printed wiring boards can be utilized as integral heat sinks by drilling holes through the laminate beneath the leadless chip carriers and filling the hole with a conductive media. This procedure allows direct heat conduction from the leadless component to the metal core and thence to the heat exchanger. Both flow-through modules and heat pipes with populated printed wiring boards bonded to both sides of the structure are an effective means of thermal management.

High Conductivity, Transparency

RF and Laser Hardening of Missile Domes

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Photograph Unavailable

Reactive sputtering of indium tin oxide (ITO) transparent conductive coatings on the iside of U.S. Army Missile domes now is a viable approach to rf hardening of laser-guided missiles. This major conclusion was reached as a result of a manufacturing methods and technology project initiated by the U.S. Army Missile Command to adapt the fusion laser coatings and coating process to the case of heat-sensitive plastics in hemispherical or conical shapes.

Battelle's Pacific Northwest Laboratory conducted the two-year project to demonstrate optical coatings, production coating equipment, and a production process for rf and laser hardening plastic missile domes used by MICOM. The primary objective of the project was transparent rf shielding based on indium tin oxide for the Army's Hellfire (polycarbonate plastic) and Copperhead (polysulfone plastic) laser-guided missile domes. Specific coating property goals included electrical sheet resistance, dome transmission, rf attenuation and adhesion. The coating equipment and processing were additionally required to permit application of other coating materials such as SiO_2 onto the same plastics for transmission enhancement, abrasion resistance, or wavelength filtering. The most challenging aspect of the project was the achievement of high electrical conductivity and optical transmission for coatings on curved plastic surfaces at lower deposition temperatures.

Battelle's achievement of high resistance to laser-induced damage in transparent conductive ITO coatings for fusion laser applications had suggested their use for both rf and laser hardening of plastic domes for laser-guided missiles and munitions. Of particular interest were the Army's missiles which are guided by radiation from Nd:YAG lasers in a wavelength falling in the region of high transparency. A single layer with the proper conductivity could provide rf shielding when the missile dome was electrically connected to the metal missile body. A multilayer interference filter, one layer of which is ITO, could provide both rf and laser hardening of the missile seeker simultaneously. The transparency of the ITO would allow hardening with minimal impact on the domes' transmission.

Batch Production Provided

Chronologically, the project consisted in scope of

- Assembly of a small coating system for coating and process development using one dome at a time

NOTE: This manufacturing technology project that was conducted by Battelle's Northwest Laboratories was funded by the U.S. Army Missile Command under the overall direction of the U.S. Army Manufacturing Technology Program office of the U.S. Army Materiel Command (AMC). The MICOM Point of Contact for more information is Mr. David Jones, (205) 876-8331.

- Design and construction of a large batch production chamber for coating thirteen domes simultaneously with automation and improved instrumentation and control.

The smaller chamber was used to demonstrate that reactive magnetron sputtering could produce ITO coatings with the required properties on temperature sensitive substrates. Hundreds of domes were coated and tested both at Battelle and MICOM to optimize the process and to develop specifications for later production coating.

The larger chamber was used to demonstrate production-scale implementation of the process at affordable costs. Other important project tasks included:

(1) Development of procedures for dome cleaning before coating

(2) Several techniques for applying metal electrodes or or contacts to the ITO coatings

(3) A process for fabricating the In/Sn sources (targets) used in the coating process and

(4) Techhiques for sheet resistance, spectral transmission, and thickness uniformity measurements on missile domes.

Hellfire domes have been hardened to greater than 30 dB shielding at the important rf frequencies with a low loss in transmission. Copperhead domes have also been coated with similar or better ITO coatings. The adherence of the coating to the plastics has been measured to be several thousand psi. Thirteen domes can be coated in 180 minutes in a vacuum deposition process involving sputtering of In/Sn metal in a reactive atmosphere. The resulting coating cost is thus about $44 per dome. Electrical contact of the ITO to the missile body requires application of a metal electrode to the threaded region of the dome. Plasma sprayed Zn, which is applied in a few minutes using a hand-held gun, works well on Hellfire domes. Some air sprayed Ag paints work equally well. Multilayer coatings of ITO and a second suitable material such as SiO_2 appear to be possible, suggesting simultaneous laser hardening by interference filtering.

Logical and orderly production implementation of the ITO coatings and processes included the following major steps:

- Environmental testing to confirm long expected coating lifetime when exposed to humidity, temperature cycling, shock, etc.
- Field testing on fired missiles
- Interaction of Battelle staff with the selected production coating contractor to ensure maximum benefit from the project.

Wider Applications Foreseen

The main conclusions of the project were (1) the technical feasibility of achieving significant rf shielding with transparent coatings less than a micron thick is unquestionably established, (2) ITO coatings can be applied to both Hellfire and Copperhead domes, (3) 30 dB rf attenuation is achieved by these coatings for frequencies in the critical range, (4) demonstrated batch production coating techniques can be used in semiautomated fashion for coating large numbers of domes, (5) batch production ITO coating costs are estimated to be about $44 per dome, (6) suitable demonstrated electrodes include plasma-sprayed Zn and air-sprayed Ag epoxy paint, and (7) SiO_2 coatings can be deposited in the same system for transmission enhancement, abrasion resistance, or wavelength filtering. The coatings and processes further appear to be applicable to virtually any electromagnetic window or dome (crystal, glass or plastic) in flat or near-hemispherical shape.

Other important project accomplishments included (1) the development of many processing procedures needed for production dome coating and evaluation such as ITO deposition parameter optimization, pre-coating dome cleaning, In/Sn source casting, and coating characterization on a curved surface, (2) the documentation of coating specifications, process and operation instructions, and equipment details, and (3) the delivery of seventy-six coated domes for evaluation by Army agencies such as MICOM and the Office of Missile Electronic Warfare (OMEW) or to the Army's dome contractor, Martin Marietta-Orlando.

A related subcontract conducted by Battelle's Columbus Laboratories demonstrated alternate approaches to transparent rf shielding for plastic missile domes. Manufacturing methods were developed for applying metallic grids or screens to the plastic domes. Two approaches demonstrated include a free-standing grid made by a modified flexible circuit board technique and a thin-film grid vapor deposited through a fabricated mask.

ITO Coatings Offer Benefits

Of all transparent conductive coatings for use in the visible and near-infrared spectral regions, the indium-tin oxide solid solution system has received the most attention to date because it simultaneously offers the highest conductivity and transmission. Maximum conductivity or minimum resistivity is usually obtained with some of the Sn replacing In substitutionally and serving as a donor impurity. Oxygen vacancies also make a major contribution to the electron carrier concentration in ITO coatings. For a given Sn content, control of oxygen deviations

from exact stoichiometry allows sensitive control of ITO conductivity.

The electrical and optical properties of the semiconductor ITO are intimately related. Generally speaking, there is a tradeoff between high optical transmission and low electrical resistivity. In addition, variation of the electron carrier concentration over several orders of magnitude, which accompanies resistivity changes, has significant effects on both the short wavelength and long wavelength transmission.

Figure 1 shows the wavelength dependence from 0.2 to 2.6 microns of the external transmittance of three ITO coatings with widely different electrical resistivities. Also shown is the transmission curve for a bare fused silica substrate. The two lower resistivity coatings are 0.63 microns thick. The high resistivity coating is 0.30 microns thick. A resistivity of 5×10^{-4} Ohm-cm is very close to the minimum value attainable for ITO. A value of 1 Ohm-cm corresponds to a coating which is nearly completely oxidized. Hence, the coatings of Figure 1 represent extremes which clearly illustrate the differences between highly conducting and semi-conducting (or insulating) coatings.

Note that all three coatings exhibit a short wavelength absorption edge in the ultraviolet spectral region due to optically induced interband electronic transitions. In general, fully oxidized ITO has an absorption edge of about 0.35 microns, which shifts to longer wavelengths near 0.40 microns as absorbing oxygen vacancies are introduced to lower the resistivity. For very high oxygen vacancy levels, the absorption edge shifts back to shorter wavelengths, as shown in Figure 1, due to a Fermi level increase caused by the very high electron concentration. The latter shift is known as the Burstein effect.

The interference pattern in the transmission curves for the coated substrates is due to constructive and destructive interference of light reflected from the air-coating and coating-substrate interfaces. Knowing the refractive index of the substrate, the index of the coating can be deduced at various wavelengths from the amplitude of the interference pattern. For the two higher resistivity coatings of Figure 1, the index is 1.80 near 1 micron and 1.85 near 0.55 micron. The refractive index is dependent on deposition conditions, however. For the low resistivity coating of Figure 1, the index cannot be deduced accurately from the interference pattern amplitude because of absorption due to the large oxygen vacancy concentration. The percent absorption loss is roughly the difference between the transmission of the coated substrate and the bare substrate near the maxima in the interference pattern.

The long wavelength absorption edge also depends on the coating resistivity, as shown in Figure 1. For the low resistivity coating, the transmission cutoff for wavelengths greater than 1 micron is clearly evident. For the high resistivity coating, little loss is detectable even near 2.6 microns. The long wavelength absorption edge in ITO is caused by metal-like free-carrier absorption which is responsible for an increase in the reflectivity and a concomitant transmission decrease. The increase in the reflectivity which accompanies the transmission decrease is shown very clearly for a highly conductive coating in Figure 2. Note that the coating absorption, defined as 100%-transmission-reflection, exhibits a peak or resonance near 1.65 micron. This long wavelength absorption edge or "plasma frequency" shifts to shorter wavelengths with decreasing resistivity. For a resistivity of 5×10^{-4} Ohm-cm, the edge is between 1 and 2 microns as shown in

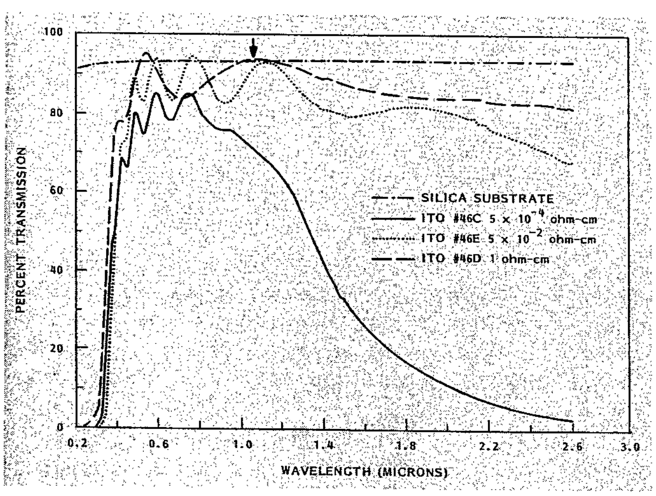

Figure 1

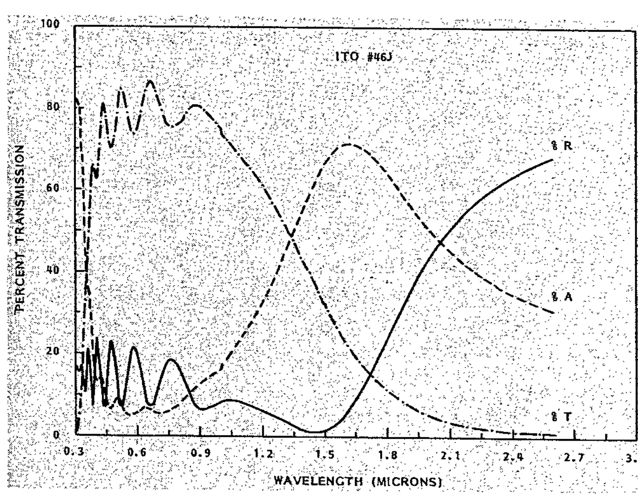

Figure 2

Figure 2. For 1 Ohm-cm resistivity, the edge is in the far infrared.

The optimum resistivity for low sheet resistance and high transmission near 1.06 microns is about .003 Ohm-cm. Thus, for a sheet resistance goal of 10 Ohms/square, the coating thickness must be approximately 1 micron. From Figures 1 and 2, it can be estimated that a coating with 10 Ohms/square resistance and a thickness of 1 micron will have a transmission loss of about 10% at 1.06 micron wavelength.

Coating Approach

Low-cost mass production coating of plastic domes with indium-tin oxide requires a coating process which gives (1) high deposition rates, (2) little substrate heating, (3) precise deposition control, and (4) uniform thickness over an approximately hemispherical shape. The coating process chosen for this work is reactive manetron sputtering with a "point-like" source. Sputtering processes in general give precise deposition control. Magnetron sputtering yields high deposition rates and little substrate heating by using a permanent magnet behind the source to efficiently ionize the sputtering gas while confining the plasma to the source region so that little substrate bombardment occurs. The small diameter or "point-like" source was chosen because it produces an approximately hemispherical distribution of sputtered material which will uniformly coat an approximately hemispherical substrate or an approximately hemispherical array of substrates.

Reactive Sputtering

Deposition of ITO coatings by reactive sputtering requires an In/Sn metal source mounted on a dc electrode inside of a vacuum chamber. Sputtering is accomplished by introducing a low pressure of an inert gas such as argon while applying a negative dc voltage to the source. A sustained discharge results and a plasma of Ar positive ions and electrons forms near the source. Attraction of Ar positive ions to the negatively biased source leads to bombardment, which in turn results in sputtering or atom-by-atom removal of material from the In/Sn source and subsequent travel to the substrate with kinetic energy in the range of 5 to 10 eV when leaving the source. Addition of a reactive gas such as oxygen to the Ar permits deposition of the oxides of the source metal by reaction with the metal atoms as they travel to the substrate or while on the substrate surface. Careful balancing of the sputtering rate for In/Sn against the introduction rate for oxygen results in the oxide composition which is both transparent and conductive.

Batch Coating System

Two versions of a small coating system were designed and built during the first year's work. The larger batch-production coating system consists of a large vacuum chamber, an automatic pumping station, and complete automatic instrumentation for precise reactive dc magnetron sputter coating. The system is shown schematically in Figure 3. The system handles thirteen Hellfire domes at a time and can be cycled two times in an eight-hour shift. All major deposition parameters are controlled by state-of-the-art digital closed-loop feedback controls. Coating thickness, dome transmission, and approximate level of oxidation are additionally monitored optically to help achieve the required coating properties and for precise end-point control.

The batch-production coating system is built around a custom made box-type vacuum chamber. The chamber is similar to many used by the optical coating industry. Vacuum-tight access through the chamber walls is pro-

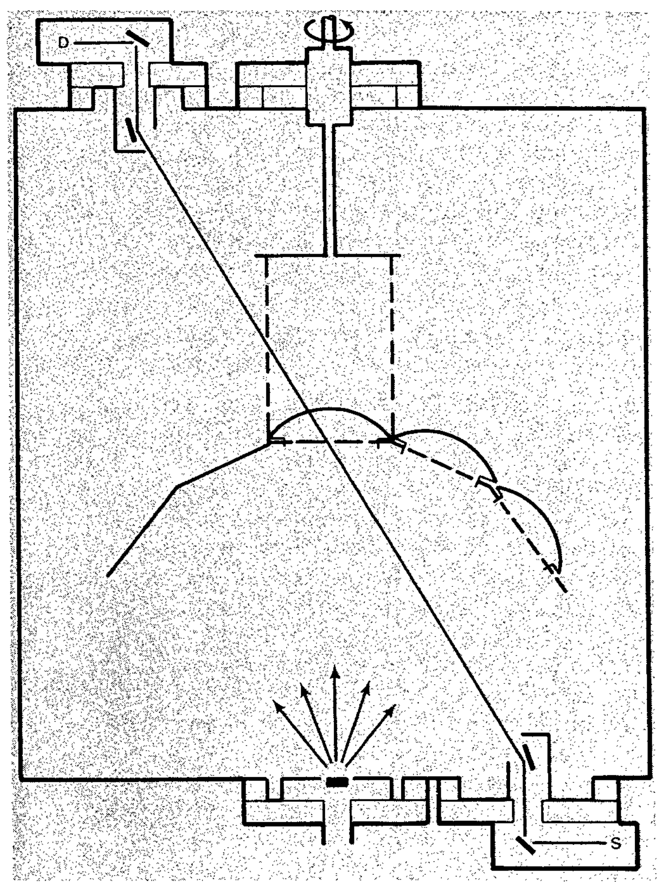

Figure 3

vided by numerous flanges. A full-size door with a captured O-ring seal gives ample access thru the front wall of the chamber for system component assembly and loading/unloading of substrates. The box chamber is connected through a goose-neck pumping stack to a conventional oil-diffusion pumping station with a liquid nitrogen cold trap and a mechanical roughing/backing pump. The pumping station is equipped with automatic valve control using both thermocouple and ion gauge instrumentation. The fully loaded chamber (including thirteen domes) is evacuated typically with the roughing pump in about 8 minutes, and further evacuated with the diffusion about 30 additional minutes.

The substrate holder visible in Figure 4 is a simple carousel suspended from the chamber top through a flange and rotated with a 12-rpm motor drive and a rotating feedthrough. The substrate holder accommodates thirteen domes in a closed-packed co-axial arrangement. The holder is constructed from welded pieces of stainless steel rod with spaces between the rods matched to the outer thread diameter of the dome for simple and secure loading. The overall shape of the substrate holder is designed to conform to a surface of constant deposition rate determined in previous chamber profiling experiments.

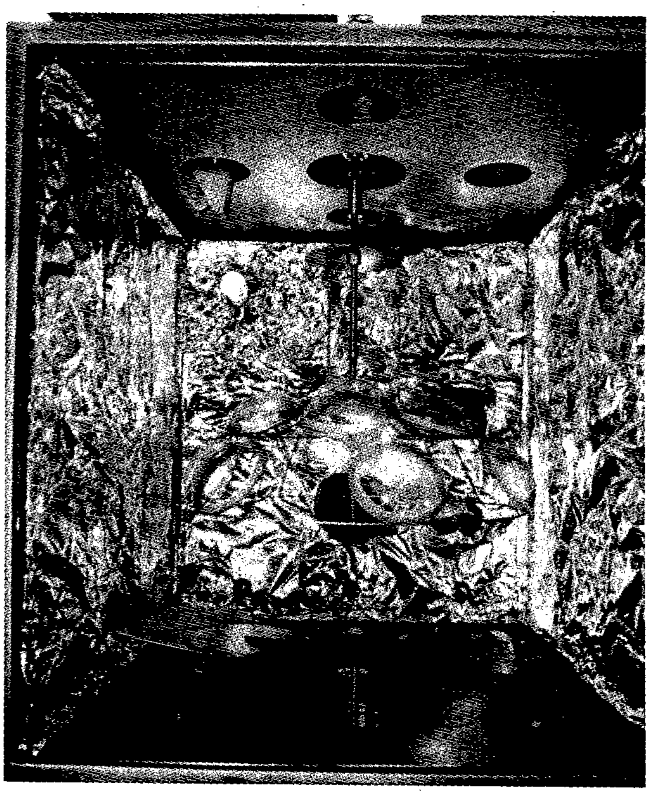

Figure 4

A rotatable shutter made of stainless steel plate welded to a stainless steel rod enters through a differentially pumped double O-ring vacuum seal on a flange bolted to the bottom of the chamber. The shutter allows cleaning, surface preconditioning, and/or stabilizing of the source before coating. The shutter is visible in Figure 4.

Three windows on the chamber door allow visual observation of the coating process, using the light of the glow discharge or an internally mounted incandescent light bulb.

The optical monitor beam-directing hardware is pictured in Figure 4, and the light path is indicated schematically in Figure 3. The light source, chopper, lens, and a 90-degree turning mirror mount on a flange on the chamber bottom. The wavelength filter, lens, detector, and a 90-degree turning mirror mount on a flange on the chamber top. Gimbaled periscopes with 30-degree turning mirrors are mounted on the bottom and top of the chamber to direct the light beam from the chamber bottom to the top through the top dome in the substrate holder. Use of the optical monitor to obtain the correct ITO coating thickness as well as instantaneous feedback on the coating properties is illustrated schematically in Figure 5.

Numerous other ports on the chamber are used for introducing argon and oxygen sputtering gases and for thermocouple gauges, ion gauges, and capacitance manometers. Argon and oxygen gases are continuously bled into the chamber during deposition through a series of valves and flow meters that provide either manual or closed-loop, automatic feedback flow control. Manual control is provided by precision needle valves which allow adjustment of the individual argon and oxygen flows from the regulated storage bottles to the chamber in flow increments. Automatic control is provided by flow ratio controller, electronic valves, and mass flow meters. The sputtering gas pressure is monitored with a capacitance manometer and is also displayed digitally by the flow ratio controller.

The power supply for the magnetron sources is a constant-current dc supply which is connected to either of the two sputtering sources through a relay-type switch. For precise manual control, the current adjust on the supply was changed from a 1-turn to a 10-turn potentiometer, and digital meters were added for precise reading of the source voltage and current. For automatic sputtering voltage control, a digital controller is used in conjunction with a stepper-motor-driven variable orifice located in the pumping station between the diffusion pump and cold trap. The digital controller is programmed to maintain constant voltage to the source by opening and closing the variable orifice as needed to adjust the sputtering gas pressure.

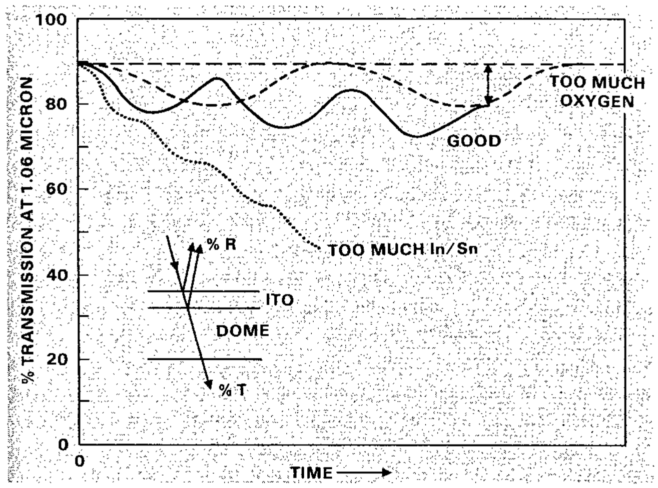

Figure 5

Sputtering Source Fabrication

For mass production coating of large quantities of domes, a supply of In/Sn sputtering sources is needed. New sources can be fabricated simply by casting into an Al mold on a conventional laboratory hot plate. The mold is machined to produce the desired target shape and size, or can be purchased. In and Sn in shot, wire, or rod form are mixed in a beaker. The beaker is placed on a hot plate and heated until all the shot melts. After stirring, the molten mixture is poured into the Al mold, which is also preheated on the hot plate. The casting and mold are then allowed to cool.

Deposition Parameters

Stoichiometric indium oxide is a transparent insulator. Adding tin as a substitutional dopant reduces its resistivity. To achieve resistivities required to meet the property goal for this project, oxygen vacancies were introduced by deliberately depositing coatings which were slightly deficient in oxygen. Since too large an oxygen deficiency will result in a metallic nontransparent coating and since too little an oxygen deficiency will result in a resistive coating, the number of oxygen vacancies must be precisely controlled.

Control of the oxygen vacancy level in reactive sputtering is achieved by balancing the rate at which In/Sn metal is sputtered from the source against the rate at which oxygen is introduced into the chamber to react with the In/Sn. The rate at which In/Sn is sputtered is controlled by two parameters: the source voltage and the source current. The rate at which oxygen is introduced is the flow. Hence, the three principal deposition parameters which must be controlled are source voltage, source current, and gas flow. Each of the three can be controlled precisely with closed-loop feedback instrumentation.

With these concepts in mind, strategy for controlling the oxygen vacancy level in ITO is easily seen to be an iterative process. First, a coating is made with the current, voltage, and oxygen flow set at values expected to yield transparent conductive ITO based on previous values used, and the coating transmission and sheet resistance are measured. If the coating is highly transparent and resistive, it is too fully oxidized. Thus, in the next deposition the current or voltage must be raised to increase the metal content relative to oxygen, or the oxygen flow must be lowered. If the first coating is metallic or dark, the current or voltage must be dropped or the oxygen flow increased. This process is repeated until the desired coating properties are achieved and the optimum deposition conditions are determined.

Systematic Tuning

Systematic tuning of deposition parameters in an iterative process to achieve the optimum tradeoff between transmission and resistance is illustrated in Figure 6. By systematically stepping through oxygen flows, a flow which produces high transmission and low resistance can be found. Note in the top curve that, at high oxygen flows, the ITO is transparent and transmission approaches that of the bare dome. At lower flows, the coatings are darker and lower in transmission. The sheet resistance curve at the bottom shows a minimum near the transition from transparent to opaque.

An alternate approach to tuning the deposition parameters is to fix the current and oxygen flow while varying the voltage, as shown in Figure 7. Note in the upper curve that low voltages result in high transmission, because at these voltages In/Sn is sputtered more slowly and is fully oxidized by the oxygen flow. At higher voltages, In/Sn is sputtered more rapidly than it can be fully oxidized and the ITO becomes dark and even metallic. The lower curve again shows that the sheet resistance exhibits a minimum near the transition from transparent to opaque ITO.

Systematic tuning data are shown in Figure 8. Note that the higher current requires a higher voltage for near optimum tuning. Also note that in Figure 8 the range of oxygen flows selected is broader than that of Figure 6, so that the ITO ranges from all metal at low flows to fully oxidized at higher flows. The resistance again exhibits a minimum near the transition point.

During the Sn content optimization work, it was discovered that the optimum oxygen flow was dependent on the source Sn content. The general dependence is shown in Figure 9.

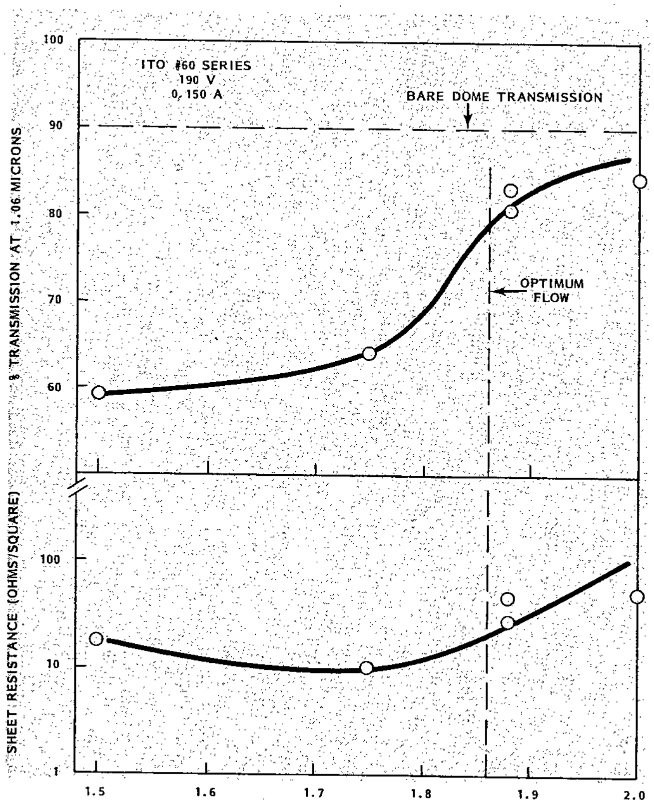

Figure 6

Parameter Tuning Aids

Achievement of the optimum conductivity and transmission for ITO coatings deposited without substrate heating requires careful tuning of the deposition parameters. In addition to the systematic plotting methods described in the previous section, several aids exist for deciding which direction to vary parameters (increase or decrease) and how much to change the parameters (increment). The aids range in type from quantitative to qualitative, and should be frequently consulted when conducting a systematic parameter optimization.

Figure 10 describes the first aid. It semiquantitatively displays the ITO coating's visual appearance and sheet resistance in the neighborhood of the optimum tuning point. At the optimum tuning point, clear coatings are obtained. If the coatings contain too much oxygen (sputtering current and voltage too low, or oxygen flow too high), the sheet resistance rises very rapidly and the coatings appear pale green or yellow to the eye. If the coatings contain too much In/Sn (sputtering current and voltage too high, or oxygen flow too low), the sheet resistance rises slowly and the coatings appear tan or brown.

The second aid is to observe after deposition the color of the source inside vertical wall. (See Figure 4). After a deposition at the optimum conditions, the source will appear a dull or matte gray with black and white specks ("salt and pepper" appearance).

The third aid, shown in Figure 11, is quantitative and is frequently helpful when first setting up the system before any systematic parameter stepping has been attempted. In this method, the source sputters onto the closed shutter with the current fixed at the value usually used, and the pumping orifice is adjusted to give a fixed chamber pressure. The oxygen flow is raised to a point expected to be well above the optimum flow, and the voltage induced on the source is recorded. The oxygen flow is then reduced in appropriate steps. At each step, the orifice is adjusted to maintain the pressure and the source voltage is recorded.

The fourth aid is presently qualitative, but could have great value if the deposition chamber were instrumented for quantitative measurements. When metal-rich coatings are being deposited, the glow region above the source is

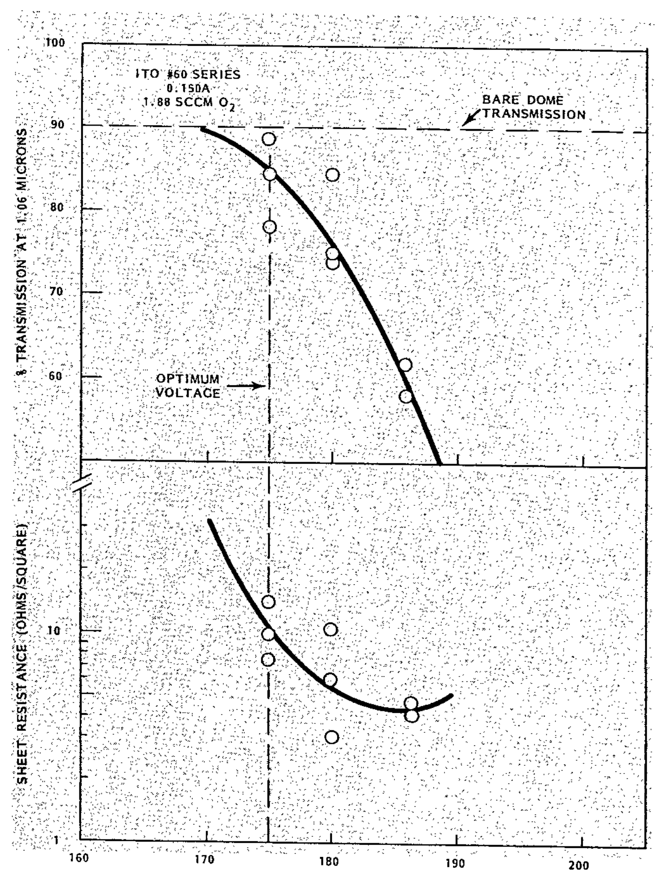

Figure 7

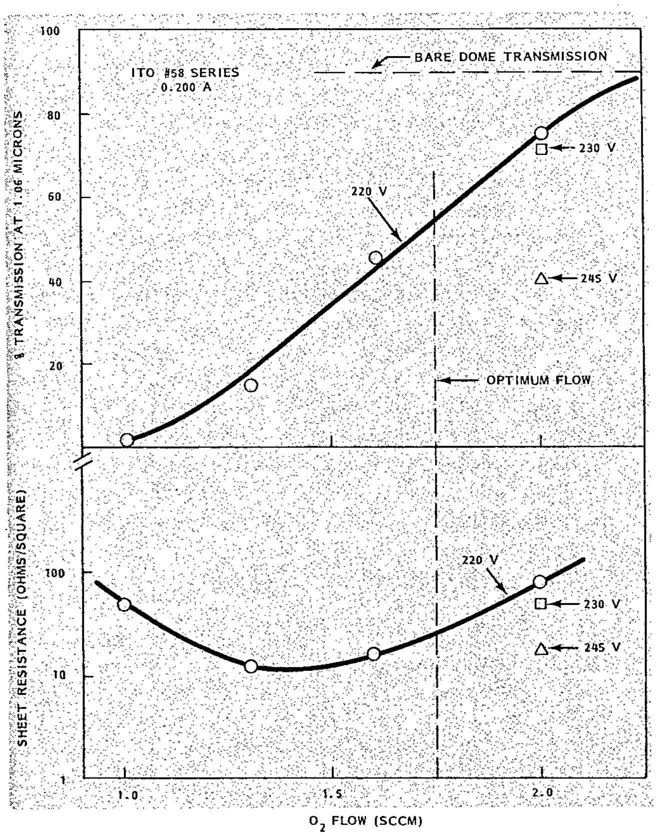

Figure 8

blue in color. When oxygen-rich coatings are being deposited, the glow region is pink. The optimum tuning point lies between these colors. The difference in colors results from the varying ratios of electronically excited metal, metal-oxygen, and oxygen species in the plasma.

The fifth aid worthy of mention is the optical monitor used in conjunction with Figure 5. Metal-rich coatings sputter rapidly and absorb noticeably with increasing thickness. Fully oxidized coatings sputter slowly with little apparent transmission loss with increasing coating thickness. Optimum ITO coatings lie between these extremes, and can be obtained more frequently if deposition conditions are fine tuned as the coating grows to produce a transmission monitor strip chart similar to that known to result for a good coating run.

Vacuum Heat Treatment Option

An alternative to controlled deposition of ITO as described above is deposition of fully oxidized or stoichiometric ITO followed by vacuum heat treatment to produce the oxygen deficiency required for conductive coatings.

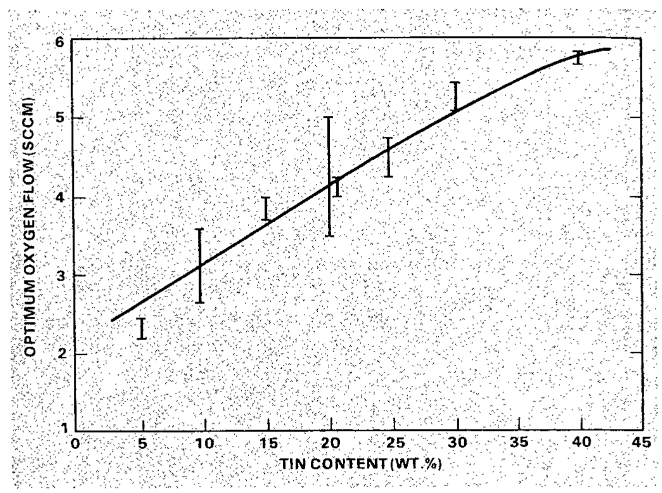

Figure 9

Optical and Electrical Characterization

Reasonably extensive characterization of the optical and electrical properties of hundreds of ITO coatings was necessary to provide guidance in coating optimization and to assess progress toward project property goals. These measurements included the following:

- RF shielding
- Spectral Transmission
- Micron Transmission
- Refractive Index
- Thickness Uniformity
- Sheet Resistance

Key Results

Figure 12 is a representative summary of the shielding levels observed for specific domes as a function of ITO sheet resistance for one frequency of importance. Each point plotted is for a separate ITO-coated dome measured on the same day.

Highest rf attentuation is obtained for the lowest sheet resistance, as expected. With increasing sheet resistance, the attenuation decreases, giving effectively no shielding (the bare dome value) for greater resistances.

Figure 13 shows transmission as a function of sheet resistance for the same domes described in Figure 12. The

lower curve marked "average" is the average of transmission measurements made at nine different, uniformly spaced points on each coated dome. The upper curve marked "maximum" is the maximum of the nine values for each dome. The transmission increases monotonically with increasing sheet resistance and approaches the bare dome value for greater resistances. The transmission decrease with decreasing sheet resistance is fundamentally unavoidable: the same electrons which lower the sheet resistance also absorb light.

The different transmissions measured at different points on a dome result primarily from coating thickness differences.

Very recently, a careful study of the influence of Sn content on the properties of ITO revealed that improved transmission and sheet resistance both result for higher Sn content.

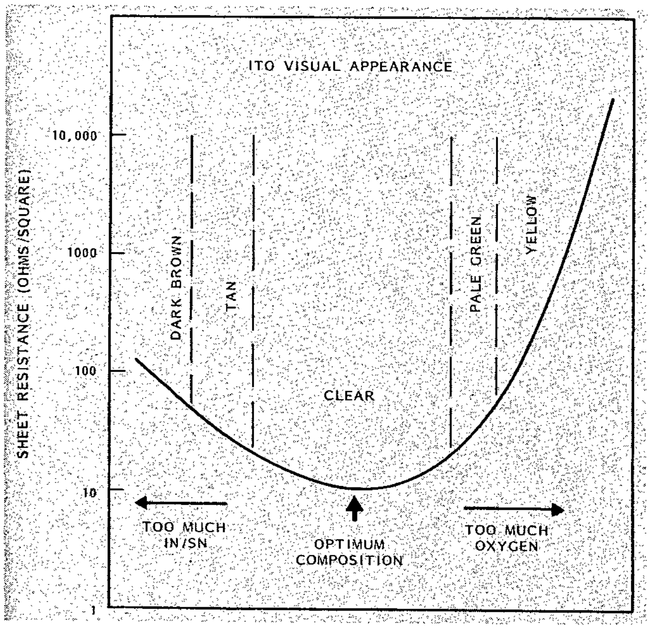

Figure 10

Potential Improvements

For applications requiring higher transmission, two improvements can be made if cost/benefit considerations warrant.

First, additional transmission can be achieved, according to calculations, by adding a low index coating layer such as SiO2 or MgF2 on top of the ITO to make a two-layer antireflection coating for one side of the plastic. (The transmission loss of the plastic is primarily Fresnel reflection).

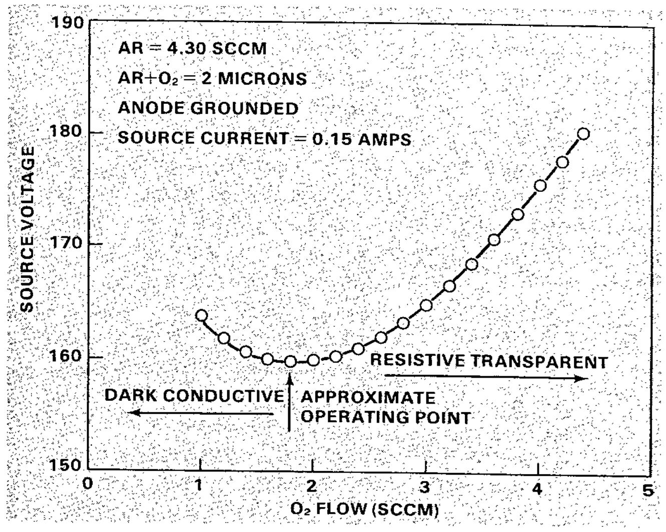

Figure 11

Second, additional transmission can be achieved by adding a single low-index layer of appropriate thickness to the outside of the dome. SiO2 and MgF2 are again promising candidates. Use of the SiO2, which is much harder than polycarbonate, may simultaneously improve the scratch and abrasion resistance of the polycarbonate domes.

All coated domes made in the project were measured for sheet resistance, spectral transmission, coating thickness, and transmission. Domes coated in the second year were, in addition, characterized for sheet resistance uniformity and transmission uniformity by measurements at a minimum of nine different points on each dome. Adherence to polysulfone and polycarbonate was measured on selected samples. Domes were then sent to MICOM for rf shielding evaluation.

Electrode Selection and Application

A metal electrode is required to ensure electrical contact between the ITO and the missile body. The coil housing to which certain coated domes are threaded during missile assembly is conductive on its exterior surface and contacts the outer flat surface of the domes. Since the ITO coatings are applied only to the inside of the domes, a metal electrode is needed to contact the ITO with this outer flat surface. Contact requires continuity across the dome threads. For some domes, the threads are inside the dome and the entire coil housing is metal.

The electrode problem and the electrode geometries selected to solve the problem are illustrated in Figures 14 and 15 for polycarbonate and polysulfone domes. Each dome is first coated on the inside with ITO.

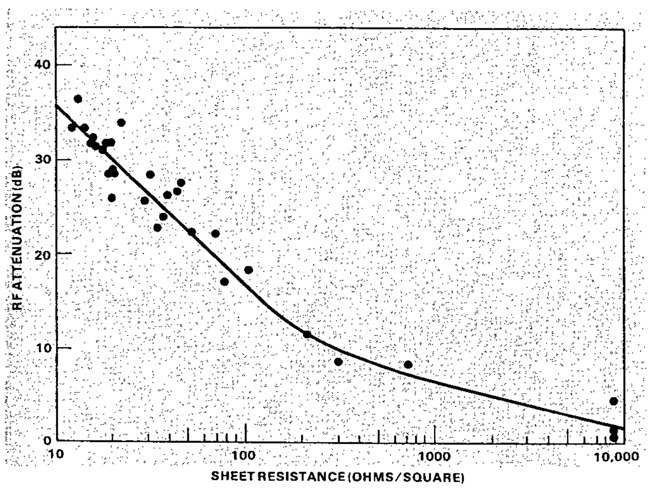

Figure 12

To electrically mate with the conductive coil housing, the Hellfire electrode must extend and be electrically continuous across the outermost flange surface, through the threads, across the bottom flat surface, and up inside the dome to the beginning of the optical surface. The thickness of the electrode should not be more than standard machining tolerances (a few 0.001 inch) to avoid problems when the dome is threaded onto the coil housing. If the coil housing were made of metal or conductively coated across its top gasket groove, it might not be necessary to coat the threads of these domes, thus greatly simplifying electrode application.

The polysulfone dome electrode requires continuity only through the threads so that the ITO coating above the threads contacts the all metal coil housing when the dome is screwed into place. However, some additional contact may be achieved by extending the metal below the threads and across the dome bottom surface. For additional rf shielding, the electrode on this dome can be extended up the interior surface to the optical surface.

Selection Criteria

Two properties appear to be important to the performance of a dome electrode material. For good electrical contact and good rf shielding, low electrical resistivity is imperative. To resist galling in the threads after screwing on and off several times, hardness or abrasion resistance also appears to be an important electrode property.

The process of applying the electrode similarly must meet several criteria. First, it should be low in cost compared to the ITO coating. Second, it must be compatible with chemically sensitive and temperature sensitive plastic dome materials. Third, it must readily permit coating of complex geometries such as the threads and both inside and outside surfaces of the dome.

Four materials and four different processes were evaluated in the project. The processes include two spraying techniques (plasma spraying of Zn and air spraying of Ag paints), one dip technique (electroless Ni plating), and one vacuum metallization technique (sputtered Ni). The spray techniques worked the best, and appear to meet all the process criteria listed above. Electrodes made by these processes further performed well in rf sheilding tests conducted at MICOM. The dip technique produced poor adhesion due to chemical incompatibility. The vacuum technique could not produce continuous metallization across the threads as expected from its "line-of-sight" deposition nature.

Plasma Sprayed Zn Electrode

Plasma spraying is a very rapid, low cost method for applying a Zn electrode to plastic. Zn is sprayed in fine molten droplet form when it is controllably introduced as a powder into a stream of ionized compressed Ar/He passed through an electric discharge gun. With this technique, the electrode on the polycarbonate domes was applied to a thickness of 0.001 to 0.002 inch inside and outside of the domes in about 3 to 6 seconds with the dome spinning on a rotating table. The setup is shown in Figure 16. A polycarbonate plug was inserted in the dome and held in place with simple tension fasteners to prevent coating the optical surface.

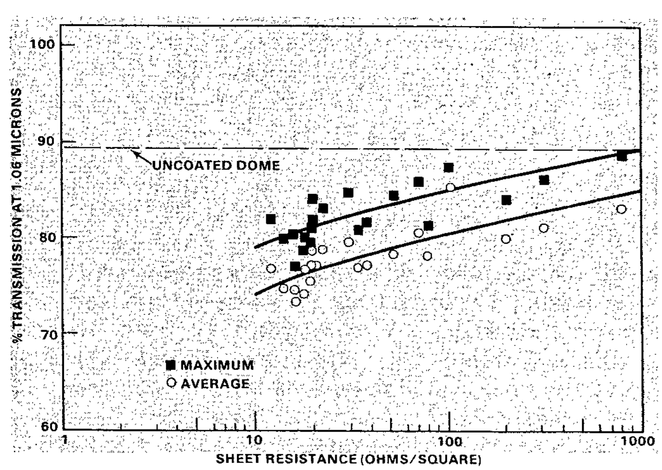

Figure 13

Air Sprayed Ag Paint Electrodes

The paint spraying process is similar in many respects to the plasma spraying approach described in the previous paragraphs. The dome is again mounted on a rotating table and the electrode is deposited to a thickness of 0.002 inch using a hand held spray gun, as shown in Figure 17. A polycarbonate plug is again inserted to protect the dome's inside optical surface, but no fasteners are required to hold the plug in place because of the more gentle nature of the paint spray.

Advantages of the paint electrode over the Zn electrode are: (1) much lower initial equipment purchase costs, roughly \$200 vs. \$17,000, (2) elimination of the grit blasting step, which reduces processing costs and eliminates some grit damage to the optical surface of the dome, (3) expected electrochemical compatibility with the silver impregnated O-ring used on the mating missile coil housing, and (4) low particulate generation.

Disadvantages of the paint electrode over the Zn electrode are: (1) longer processing times including spraying, double coating, time between coats, and curing at elevated temperatures, (2) higher sheet resistance for the same thickness, (3) inconsistent sheet resistance results, and (4) chemical incompatibility between the paint thinner and polycarbonate or polysulfone. Key to the success of the paint spray approach for the Hellfire thread region is a highly conductive and abrasion resistant paint.

Electroless Ni Electrodes

Electroless Ni plating was investigated briefly as a potentially low cost technique for coating threads by submersion in a coating bath. Electroless Ni plating is the catalytic reduction of Ni ions in an aqueous solution of hypophosphite ions. The Ni reduction takes place on the surface of the catalyst.

Sputtered Ni Electrodes

Ni in smooth, hard, shiny and conductive form is easily deposited by sputtering on many substrates, including plastics. Ni coating of missile dome electrodes by sputtering, however, is difficult because the threads are not accessible to line-of-sight deposition. Ni electrodes were attempted on several domes of each type by sputtering so that rf shielding tests could be carried out on the ITO coatings. Deposition was made at much higher sputtering gas pressures than normally used so that collisions of sputtered Ni atoms with Ar atoms might scatter Ni into thread regions not accessible to line-of-sight incidence. This approach appeared to work in that the threaded area was

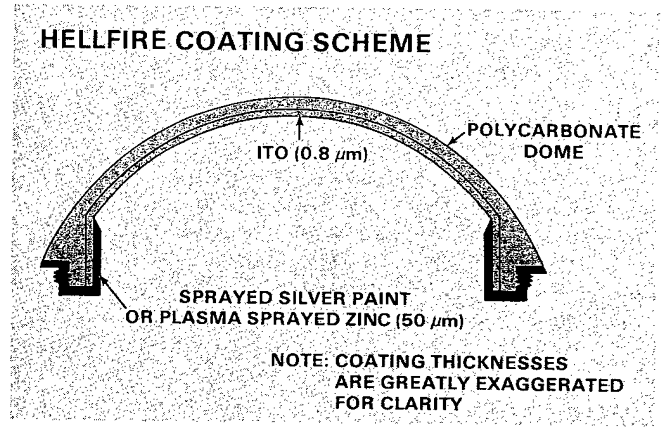

Figure 14

visibly coated and dc resistance measurements across the threads indicated only a few Ohms. However, sputtering at high gas pressures is impractically slow, and the Ni in the threads appears to wear poorly when threaded to an unthreaded from the coil housing several times, so that other contacts should be sought.

Dome Cleaning and Precoating Preparation

Many cleaning solvents and procedures were examined throughout the first year of the program to (1) remove fingerprints and other grease, (2) maximize coating adhesion, and (3) avoid "water spots" left on the dome after drying. The essence of the problem is that both polycarbonate and polysulfone degrade rapidly (explosively) in all common laboratory degreasing solvents such as acetone, trichloroethylene, and benzene. Weaker solvents such as freons and alcohols do not harm the domes, but they do not remove fingerprints, either. An interesting and potentially useful observation was that polysulfone was much easier to clean then polycarbonate. Polysulfone domes appeared to be hydrophobic; aqueous cleaning solutions bead or form drops and roll off the dome when tilted, leaving no water spots.

Acid Etching

In first year work, both polycarbonate and polysulfone appeared to be unaffected by inorganic acids over a period of minutes to several hours at room temperature. Hence, ITO coatings not meeting performance specifications were etched off. After drying, the domes were recoated.

In second year work, it was consistently noted, however, that acid etching caused three problems. First, coating adhesion was diminished. Coatings on re-used domes invariably develop (sometimes weeks after deposition) a network of fine microcracks in a circular region about

halfway down the optical surface from the dome top. The cracking does not appear to affect either transmission or rf shielding, but it may indicate a reduction in expected coating lifetime. Second, transmission of the bare dome drops with exposure to acid. Third, the domes develop a yellow color, indicative of increased absorption by polycarbonate in the blue-green region of the visible range.

The conclusion is that etching in HCl is acceptable for re-use of practice domes, but not for domes which must meet transmission, shelf life, and field life specifications.

Deposition Rates

Typical deposition rates when coating domes one at a time or in batches of thirteen depend on four factors: (1) coating stoichiometry, (2) power applied to the source, (3) source to substrate spacing, and (4) age of the source.

The influence of coating stoichiometry on deposition rate arises from the differences in sputtering yield for metals and oxides. Here, sputtering yield is the number of atoms removed from the source for each incident positive Ar ion.

Deposition rate also depends approximately lineraly on source current, since the source current is the number of ar positive ions incident per second and these same ions produce the sputtering.

Deposition rate varies approximately as the reciprocal of the square of the source-to-substrate spacing, for spacings between 6 and 16 inches. This type of behavior is expected from the point-source nature of the sputtering gun.

Age of the source also influences deposition rate through the development of an increasingly wider and deeper ring erosion pattern. The larger erosion pattern is believed to reduce the amount of sputtering per unit area of source surface so that more oxide forms and lowers the sputtering yield.

Thickness Uniformity

Optical thickness uniformity is important to dome coating performance because it influences both the uniformity of transmission across the dome surface (through interference effects) and the sheet resistance (through geometric effects).

When coating domes one at a time with the optimum source-to-substrate spacings, the top was always thicker than the bottom of the dome's optical surface and the thickness decreased monotonically from top to bottom.

When coating domes in batches of thirteen, thickness uniformities were always better than for the single dome deposition case, but appeared to depend on the age of the source.

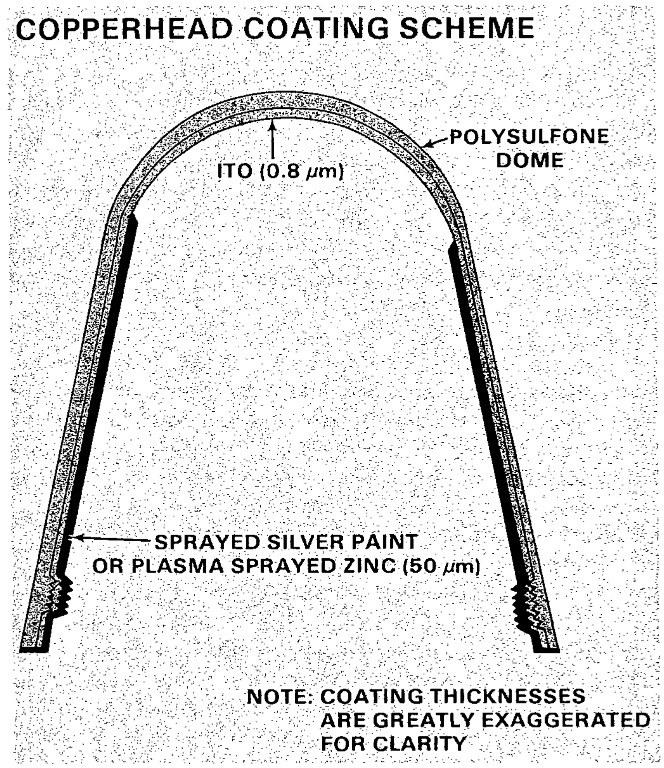

Figure 15

Chamber Rate Profiling

A surface of constant deposition rate is imperative to the proper design of a multidome holder so that all domes receive the same coating thickness.

Using the rotating substrate-holder feedthrough shown in Figure 4, an array of polycarbonate strips is suspended from a rotating threaded rod with a cylindrical spacer. The strips are arranged so that their distance from the source ranges in 1 inch steps, so that each strip causes minimal blocking of the coating flux arriving at the others (spaced angularly). With the entire array rotating, the strips sweep out all useful substrate area from chamber center to edge. A coating deposition is then carried out.

SiO_2 Coatings

Preliminary deposition of SiO_2 coatings was examined to demonstrate that the same equipment and techniques used for ITO could be used to deposit other oxide optical coating materials. SiO_2 is particularly useful because (1) its low refractive index complements the ITO high

index, so that the combination can be used for multilayer antireflection or filtering design and (2) its low refractive index permits its use as a single antireflection coating for the outside of plastic domes. In the latter application, the SiO2 coating is expected to also provide scratch and abrasion resistance for the relatively soft plastics.

Deposition rates are lower for SiO_2 than ITO for comparable source currents and voltages. Deposition proceeds less smoothly as well, with noticeable small arcs occuring near the source surface, especially at higher source power levels. However, the antireflection coating on the dome outside is more than four times thinner than the ITO coating. The SiO_2 thickness required for a two-layer SiO_2/ITO antireflection coating for the dome inside is similarly thin.

Properties

SiO_2 coatings on missile domes exhibited excellent transmission to the eye and lossless transmission throughout the visible and near infrared regions. A 3% transmission enhancement was measured, demonstrating that the single-layer antireflection concept works.

Adhesion of the SiO_2 to the polycarbonate appeared to be excellent. There was no evidence of cracking or peeling. Although no quantitative measurements were attempted, the qualitative hardness of the SiO_2 coatings appeared to be good based on simple scratch tests with a hard, sharp probe.

Cost/Benefit Analysis

The benefit from applying a single ITO coating to a missile dome is rf or EMI shielding protection of about 30 dB while still retaining approximately 90% of the dome transmission. If multilayer coatings are applied, the benefit is transmission enhancement at desired wavelengths or filtering to reject or diminish unwanted wavelengths. If a coating is applied to the dome outside benefits are transmission enhancement and scratch or abrasion resistance for the soft plastic.

Capital Equipment Investment

The exact equipment cost depends upon whether production coating equipment already exists in precisely the form needed, already exists but requires some modification, or does not exist at all and must be purchased and assembled completely. Thus, the capital investment required is bounded by zero (for the first case) and the cost of reproducing part-for-part the batch coating system and electrode spraying equipment demonstrated in this project (for the third case).

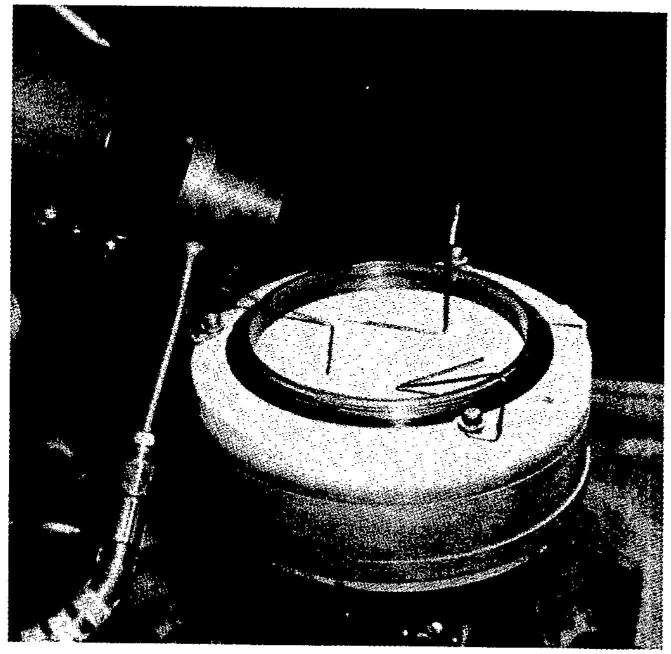

Figure 16

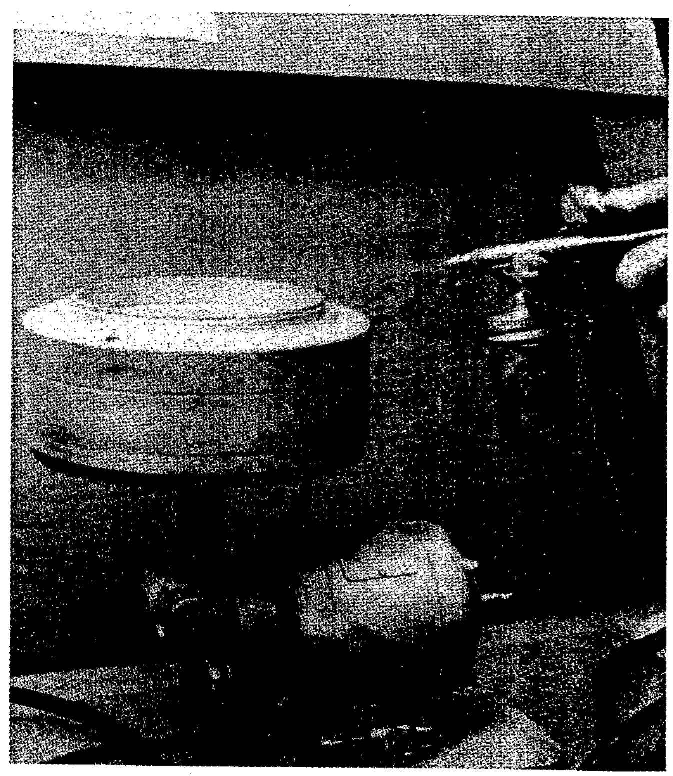

Figure 17

Operation Costs

Much of the coating process is automated and usually only requires one operator for opening the shutter to start the coating run and for shutting off the equipment when the correct thickness is achieved. Hence, the ITO coating process is a single-man operation, and the cost per dome for applying the ITO is determined by the number of domes that can be coated in one day by that operator.

With the batch coating system described in this report, thirteen domes are coated simultaneously and two batches can be coated in one day. Fully burdened costs (including all management and facilities overheads) are expected to be about $70 per hour or $560 per day for an experienced coating system operator. Thus the coating cost per dome is $22, assuming 100% success yield. For 50% coating success yield, the cost is $44.

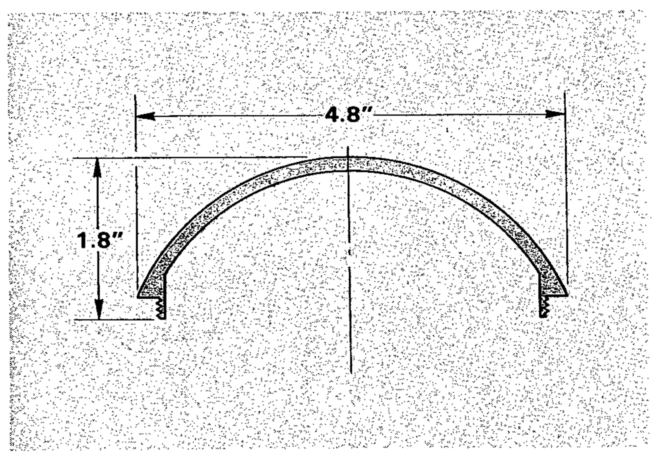

Figure 18

Other Uses of Results

The coating, coating equipment and coating processes demonstrated in this project are expected to be applicable to many other domes and/or windows in Electro-Optic or laser guided missiles or munitions used by the Army, Navy or Air Force. Examples are (1) laser guided bombs, which use seekers very similar to those used in Hellfire and Copperhead missiles, (2) terrain identifying cruise missiles, and (3) camera-guided air to air and air to ground missiles. Other important potential applications include (1) heat rejection and antistatic coatings for plastic aircraft canopies and (2) de-icing and de-fogging coatings for plastic aircraft windows.

Specific commercial applications have not yet been investigated, but the coating and shielding developed here will be useful wherever protection from rf or EMI is needed simultaneously with light transmission at visible or near infrared wavelengths. Possible commercial applications include (1) transparent rf shielding for the windows of household microwave ovens and (2) transparent EMI shielding for the digital display windows of computers, calculators and other instrumentation. De-icing and de-fogging coatings for plastic aircraft windows of commercial aircraft are of course a third application.

Technology Transfer

The contractor for this project can very ably transfer the relevant technology to a suitable commercial entity so that maximum return on the Government's investment is realized. Contractual arrangements for such a technology transfer can be readily made with that contract research organization.

Suitable commercial entities for coating technology transfer include most commercial optical coating firms in the United States. Many of these firms are also familiar with the transparent conductive coatings that have been developed in the project for rf hardening. However, none of these firms have much experience with the reactive sputtering technique required for the unusual substrate materials. Thus, emphasis in the technology transfer would therefore be placed on instruction and familiarization of the selected firm(s) with the sputtering process. Other possible commercial entities to which the technology can be transferred are the firms which presently manufacture domes for the Army.

Four key areas for technology transfer as it relates to this project are (1) coating equipment, (2) personnel training, (3) consultation, and (4) further research or development.

Optional Manufacturing Techniques

In a subcontract with Battelle-Northwest, Battelle's Columbus Laboratories demonstrated a manufacturing method for placing metallic grids on plastic nosecones. Four prototypes and an evaporative mask were delivered for test and evaluation.

This work was based on a Battelle-developed process (now in production) for producing low-cost flexible printed circuits (patterned copper metal on plastic). Battelle-Columbus has a unique facility for this process and, through this effort, has shown that it is applicable to placing patterned metallic structures on the curved surfaces of missile nosecones. A follow-on effort is recommended to optimize the process and determine the manufacturing cost/benefit factors.

The missile nosecone prototypes delivered transmit in the near IR and reflect long wavelength RF. The metallic grid is placed on the inside surface of the nosecone.

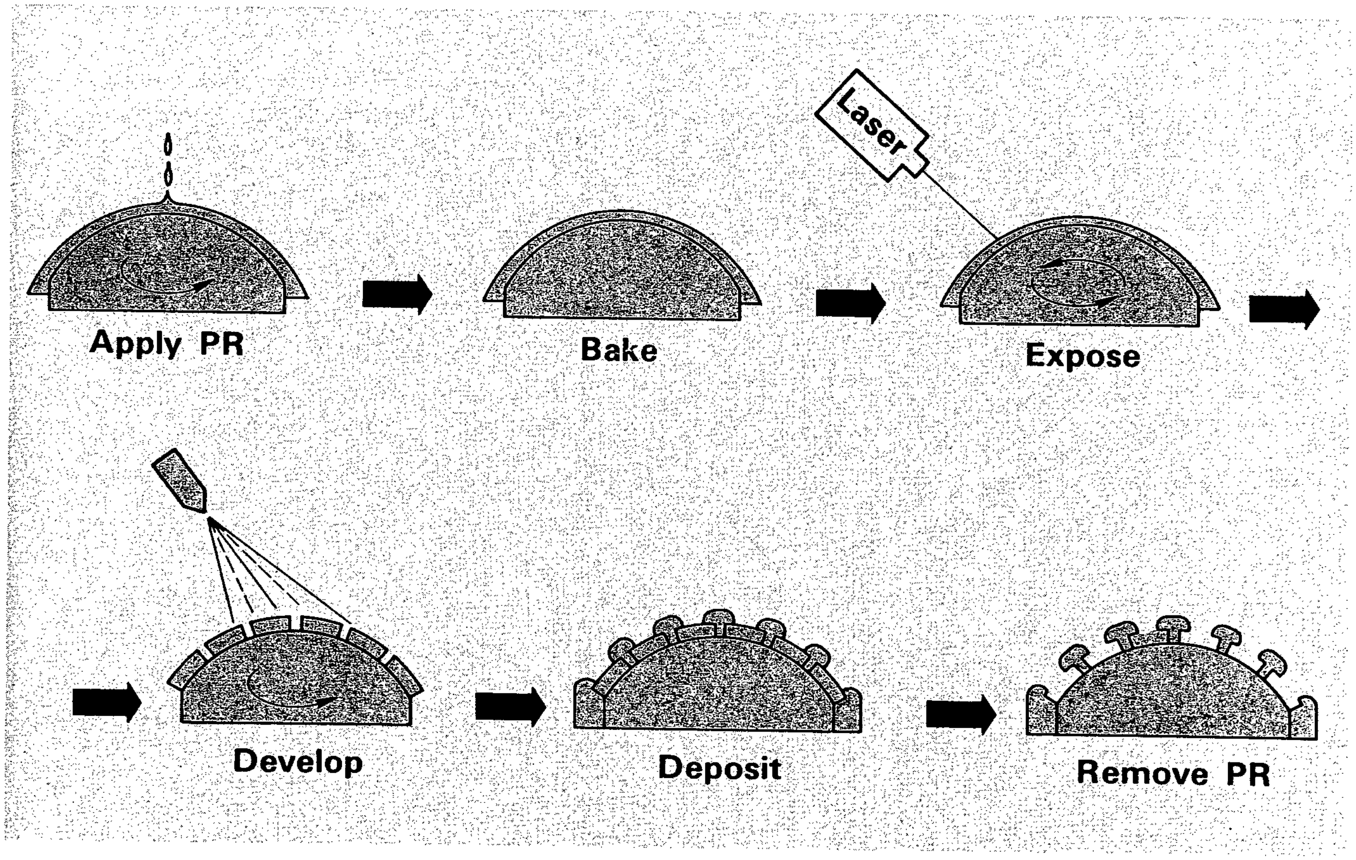

Figure 19

The nosecone geometry is shown in Figure 18. The spherical section is truncated by a radius cylinder and threads are located on the outside of the cylinder. The material is polycarbonate.

Fabrication Process

The grid fabrication process is outlined in Figures 19 and 20. The first step illustrated is the application of positive photoresist to a stainless steel mandrel.

The mandrel has been cut to fit inside a prefabricated polycarbonate nosecone accommodating the metallic grid thickness.

After cleaning the mandrel is spun and the photoresist is applied. Spinning tends to spread the resist to create a uniform coating over the entire surface. The resist is baked dry and after cooling, the mandrel is ready for exposure.

Exposure is accomplished with an ultraviolet laser focused to a spot on the mandrel surface. The mandrel is manipulated, rotated, raised, and rotated in a regular fashion to scan over the predetermined grid pattern. The laboratory apparatus is illustrated in Figure 21. The lens must be indexed slightly with each elevation in order to maintain a constant spot size.

The next step of the fabrication process, as shown in Figure 19, is to develop the photoresist. After exposure the mandrel is placed in a spray booth and spun slowly. Spraying is done at room temperature. Inspection verifies that the lines have cleared, and, after drying, the mandrel is ready for electroplating.

The final step of fabrication is to make provisions to electrically connect the grid to the missile body. The method used in this program was to paint the nosecone rim and threads with conductive epoxy.

Evaporative Grids

A totally different fabrication technique was proven and this optional process remains as a backup technique. The evaporative process is illustrated in Figure 22. A mask is inserted into the nosecone and metal is sputtered or vapor deposited through the open areas of the mask.

The mask was fabricated with the same process described above and in Figures 19 and 20. The mask consists of 50 parallel slots in a thick Ni shell. Fabrication of a square grid requires two vapor depositions; the second after the mask is rotated 90 degrees. One evaporative grid prototype nosecone and the mask were delivered for evaluation.

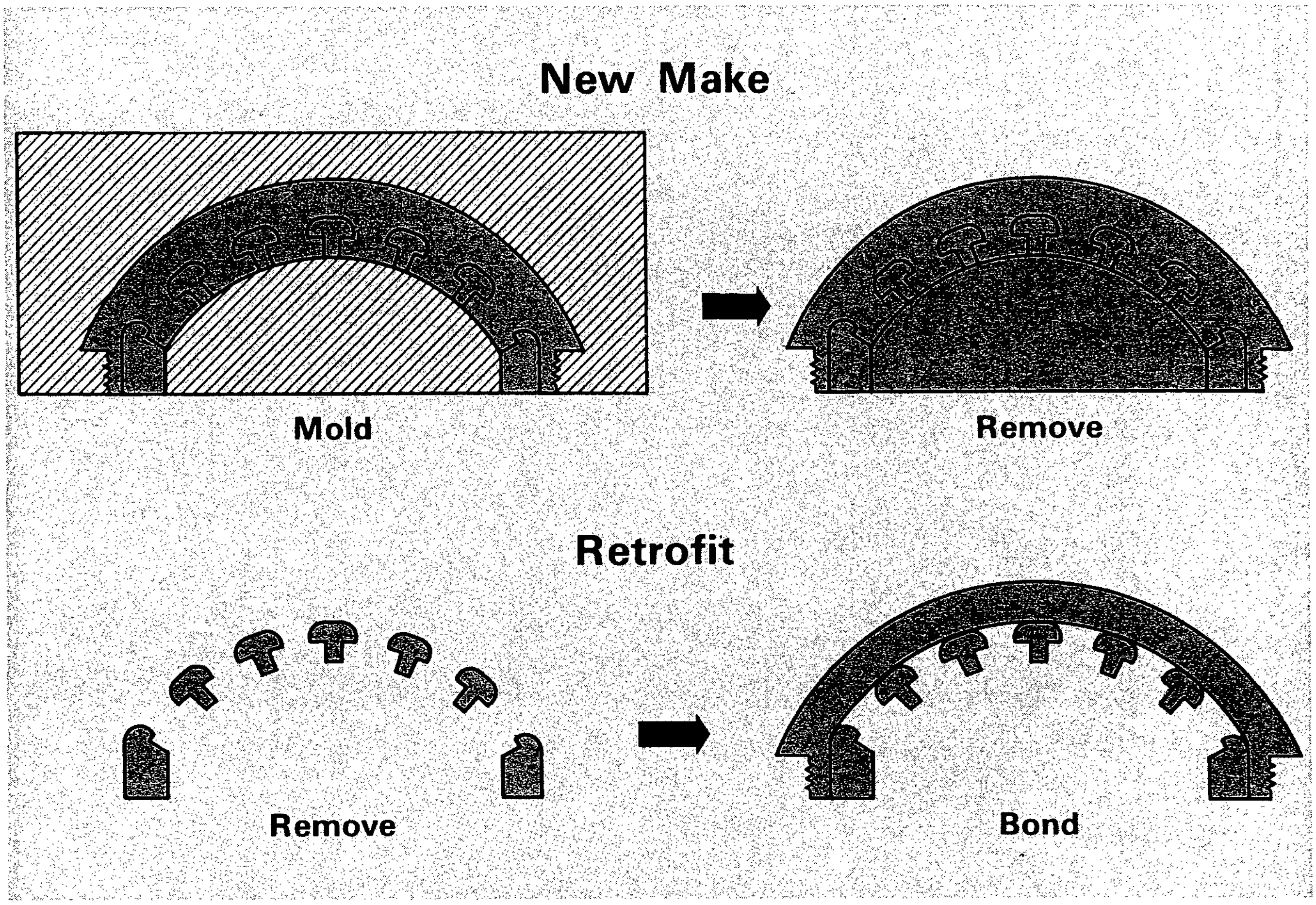

Figure 20

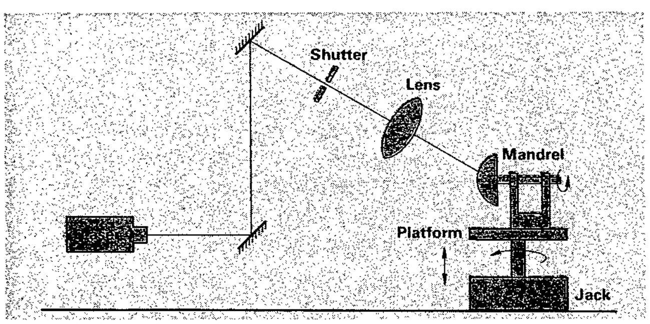

Figure 21

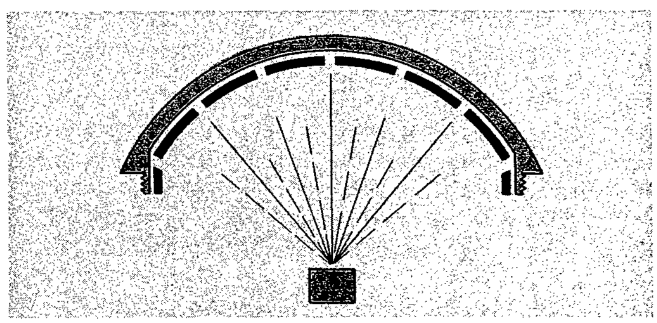

Figure 22

Conclusion

Demonstrated was a manufacturing process for placing fine metallic grids on the curved surface of the plastic nosecone. The process is based on a low-cost flexible circuit board fabrication technique. The metallic mesh process may be used either for new nosecone fabrication or for retrofit of existing nosecones. Three retrofit nosecones were delivered for evaluation.

An alternative process was briefly considered, also. This involves vapor deposition of the grid directly onto the plastic nosecone. An evaporation mask was fabricated using the retrofit process described above. The mask is similar to the negative of a grid.

The advantage of the metallic grids are several: rugged, simple construction and effective; the process looks very economical and very promising.